Design and Analysis of Intelligent Navigational Controller for Mobile Robot

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Design and Analysis of Intelligent Navigational Controller for Mobile Robot

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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Certificate

*This is to certify that the thesis entitled, **Design and Analysis of Intelligent Navigational Controller for Mobile Robot**, being submitted by Mr. Krishna Kant Pandey, Roll No. 611ME312 to the Department of Mechanical Engineering, National Institute of Technology, Rourkela, for the partial fulfillment of award of the degree Master of Technology (Research), is a record of bona fide research work carried out by him under my supervision and guidance.*

This thesis in my opinion, is worthy of consideration for award of the degree of Doctor of Philosophy in accordance with the regulation of the institute. To the best of my knowledge, the results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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Abstract

Since last several years requirement graph for autonomous mobile robots according to its virtual application has always been an upward one. Smother and faster mobile robots navigation with multiple function are the necessity of the day. This research is based on navigation system as well as kinematics model analysis for autonomous mobile robot in known environments. To execute and attain introductory robotic behaviour inside environments (e.g. obstacle avoidance, wall or edge following and target seeking) robot uses method of perception, sensor integration and fusion. With the help of these sensors robot creates its collision free path and analyse an environmental map time to time. Mobile robot navigation in an unfamiliar environment can be successfully studied here using online sensor fusion and integration. Various AI algorithm are used to describe overall procedure of mobile robot navigation and its path planning problem. To design suitable controller that create collision free path are achieved by the combined study of kinematics analysis of motion as well as an artificial intelligent technique. In fuzzy logic approach, a set of linguistic fuzzy rules are generated for navigation of mobile robot. An expert controller has been developed for the navigation in various condition of environment using these fuzzy rules. Further, type-2 fuzzy is employed to simplify and clarify the developed control algorithm more accurately due to fuzzy logic limitations. In addition, recurrent neural network (RNN) methodology has been analysed for robot navigation. Which helps the model at the time of learning stage. The robustness of controller has been checked on Webots simulation platform. Simulation results and performance of the controller using Webots platform show that, the mobile robot is capable for avoiding obstacles and reaching the termination point in efficient manner.

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Chapter 1

INTRODUCTION

1.1 Introduction

"One, a robot may not injure a human being, or through inaction, allow a human being to come to harm; Two, a robot must obey the orders given to it by human beings except where such orders would conflict with the First Law; Three, a robot must protect its own existence as long as such protection does not conflict with the First or Second Laws."

Laws of Robotics by Isaac Asimov

A robot may be defined as *'a mechanical device which executes automated jobs based on either human observation or a set of universal rules, using artificial intelligence techniques'*. The first commercial robot was developed in 1961 and used in the automotive industry by Ford. The robots were principally intended to replace human in monotonous, heavy and hazardous processes.

In universal aspect, "Mobile Robot" may be defined as 'a combination of automated based control structure with sensing element, intelligence, and mobility'. On the other hand, cognition, perception, action (by actuator), localization, and learning are essential gears of the autonomous mobile robot. Due to navigation tendency, which deliver flexibility in use towards challenging applications such as warehousing robots, micro-robots, service robots, and guard robots but not limited, it's very popular. Robot navigation is a vast field and can be divided into subcategories such as indoor and outdoor navigation for better understanding of the problems it addresses.

The study about the mobile robot is mainly categorized in three classes such as trajectory planning, position estimation (localization) and motion control. With these several cases dynamic models help to get the objective, but it may be difficult as it holds information of the torques or forces. On the other hand, for cases related to these paradigms; kinematics may help to find the objective as well as easier to obtain since it does not involve any statistics related to torques or the forces.

Mobile robots need to develop communication with environment through sensors module. They use online intelligence technique to determine the finest action to take. The development of intelligent navigation systems on mobile robots is still at the centre of several research projects to smother, shortest, collision free and optimal path as a solution.

Autonomous systems have the capability to deal with ambiguity and adjust itself according to environment by learning. Uncertainty may come up from many sources, but it should cope with vagueness every time. The overall structure of this thesis to provide informations; how to discover contemporary learning methodology, which are dominant at the stage of online learning.

This research work has been described with respect to the mobile robot and briefly provide behavioral information of navigation system for different real world environments. This chapter briefly describe the background information and concerning work which carried out in this thesis as well as presents basic overview related to mobile robot research and offer the sources of inspiration. In addition, third part of this chapter has been clarify the overview of major goals of this research i.e. what type of challenge have been undertaken and how, which are restated later in more depth in the successive chapters. An outline of current research work has been sketched in last section of this chapter.

1.2 Background and Motivation

To conduct work with any type of machine which produce output, it needs to be actuated first with precision rate. The actuation means, covers a part of mechanism or machine inside which may be inputted mechanical work transformed into desired useful work output. Similarly, a robot is an autonomous system that can be able to sense its environment, and to act on it to achieve goals. A mobile robot adds the fact that it is not confined to one specific location, as it has the capability of moving in its environment.

In 1950, Asimov [1] introducing the three laws of robotics, after introducing these laws Asimov can't satisfied with this. Accordingly, he extend his first law, which protect individual humans. This law is greater than first law i.e.: "A robot may not injure humanity, or through inaction, allow humanity to come to harm".

The latest argument from the most primitive, regarding the development of autonomous mobile robot, it comes with pre-planned mechanism, which employed in system to achieve the goal globally without human interface in ambiguous environment as well as leads the research on robot system from starting to present. Control algorithm has combined the hardware of the robot system with computational principle and enable the navigation at real time environment. To deal with large-scale environment, mobile robot is not only the collection of an algorithms for sensing real time response, amplifying knowledge, justifying the positional error and poses motion; robot have also the capacity to conduct all fashions subjected to real world. Such fictitious concepts and algorithms for mobile robot provides to check an authenticity.

Research and development of mobile robot involves the creation of new methodology with areas of engineering, computer science, biology, mining. Mobile robot has many applications, which includes automated freeway driving, guiding the blind and disabled human, work in hazardous areas where human can't survive and provides flexibility in assembled system that consists heavy mechanical parts.

Historical evaluation of the mobile robot delivers following investigation that may show the effectiveness of a robot over human:

- An unfriendly environment into which referring a human being would be either very costly (for mass production) or very dangerous (zero gravitational and atomic zone) or in an extreme instance when terrains are completely distant to humans such as atomic environment.
- In case of a task with very high fatigue factor.

Perception and action are tightly coupled in a closed loop to deposit navigational strategy of mobile agents. This attentiveness reverses the inclination of mobile robotics science in the direction of an essential interdisciplinary research area involving different disciplines such as mechanical engineering (configuring particular mechanisms), computer science (sensing and planning algorithms), electrical and electronics engineering (system integration and communications), cognitive psychology and neuroscience (biological organisms).

Mobile robots are the first intelligent system, which can perform the processes or work like a human being as well as delivered desired tasks in various (known and unknown) environments without human guidance. In addition, mobile robotics research enable the surprizing feature inside robot to survive with different environment, whether it is on land, underwater, in the air, underground or in space. To pass the stage of autonomous robot quality, the robot may has following capability and which relate it to real world of robotics:

- Maintain law of robotics, without human assistance
- Function independently and interact with human beings
- Carry out different jobs
- Re-programmable and a robot may also be able to learn autonomously
- Repair itself without outside assistance

Finally, the overall creation of mobile robotics science depends upon following categories:
Locomotion - the method of initiating a robot to move

- In order to produce motion, forces must be applied to the robot
- Depends upon motor output and payload

Dynamics - structure with study of motion in which these forces are exhibited

- Transactions with the relationship between forces and motions

Kinematics - analysis of the mathematics of motion without considering the effect of forces on motion

- Deals with the geometrical interactions that govern the system
- Deals with the connection between control constraints and the activities of a system

The main characteristic that defines an autonomous robot is the ability to act on the basis of its own decisions and not through the control of a human. Navigation is defined as the process or activity of accurately ascertaining one's position, planning and following a route. In robotics, navigation refers to the way a robot finds its way in the environment and is a common necessity and requirement for almost all mobile robots. Based on requirement, application and necessity it has been categorize as:

- Wheeled mobile robots
- Legged robots
- Aerial robots
- Underwater robots
- Humanoid robots

From the last decades, optimization cover the maximum range of research article. Apart of this, operational capability is one of them. Further, this thesis involves optimization of operational capability and related to the navigational strategies of mobile robot system. Day by day, various investigations have been made related to autonomous mobile robotics system due to simultaneous research as well as application related to multi disciplines. But, research related to the particular field i.e. path analysis and planning of autonomous mobile robot (AMR) occurring with slower rate rather than expected, compare to its rapid age of research. According to this viewpoint; research is stirred towards investigations related to real-time navigation and path analysis of autonomous mobile robot (AMR), where the robot must have capability to:

- Sense and deal with environmental data
- Understand and learn the sensed environmental data to map the future platforms
- Always perform a real-time controlled motion for known and unknown platform
- Avoiding static and dynamic obstacles without human assistance (it has ability to find an alternative route)
- To avoiding collision; maintain more clearance from the obstacle with respect to certain performance measures and execute smoother navigation
- and, map shorter path

Therefore, the path analysis and planning involves optimization with respect to certain performance measures. The navigation and control of mobile robots inside environment is a challenging topic and this requires a process of alteration to the environment.

1.3 Aim and Objectives

This research focuses on navigation and path planning for the mobile robot in a known as well as partially unknown environment. The aim of this thesis are summarized below:

The motive is to develop an autonomous mobile robotics algorithm and control physical systems according to purpose without human involvement either directly or indirectly in real-world environments. To continue working within dangerous platform and to familiarise with changing environment; the power of robust autonomy (self-governing) is essential for robotics machine. Accordingly, the robot should be intelligent to manage its sequence of action through specific perceptive process, rather than following a static, hard-wired sequence of cursorily provided commands. To deliver the maximum autonomy to the mobile robot system; presently, researchers conduct new experiment day by day.

The objective of this research is to find the shortest and safest path in a dangerous environment, from the origin of the robot to its termination point and it is one of the essential requirements for the robotics system. In addition, we have implemented an advanced algorithm for efficient navigation of mobile robot.

Attempt has been made to develop and implement an intelligent rule based fuzzy logic control algorithm for navigation and path planning for mobile robot in known and partially unknown environment.

In this thesis, combined effect of rule base and fuzzy logic has been considered for navigation as well as for path planning. The generated alternative path should deliver the optimal works. To develop the robust methodology for searching the initial feasible path in efficient manner; we have developed rule based fuzzy logic approach.

The thesis aims to explore and improve the navigational and path planning algorithm performance for real time mobile robot. Several algorithm has been simulated and investigated using webots simulation software. When an obstacle is detected on the path two-step planned process is activated for path planning. The goal of this thesis is to obtain optimal path with minimum processing time and collision free navigation for known and partially unknown environment.

For navigation of robot the following point should be considered:

- To navigate freely and safely inside environment

- To accomplish a number of dissimilar tasks
- To learn from experience and change its behaviour accordingly
- To build internal representation of its world that can be used for reasoning processes like navigation
- Finally, to choose the most appropriate path, addresses the human intelligence for finding a way towards termination point

Due to the limitations of fuzzy logic for mobile robots navigation, the type 2 fuzzy logic is presented, which permits the robot to accomplish the advanced control architecture inside the working location and attain the termination point more proficiently and effectually with minimum time using sensor based online direct path. Thereafter, conclusion has been made; the path obtained by type 2 fuzzy logic technique is superior, rather than previously obtained path and this conclusion is generated through number of theoretical simulation examples, which are conducted on Webots simulation platform. Whenever, this algorithm is applied through mobile robotic platform; it enables the mobile robot to move freely inside environment and robot search for a more satisfactory path between local to termination point. A recurrent neural network technique for mobile robot navigation is also studied here. The results of navigation proves its efficiency over previous methodology. Results shown that its accuracy is high as well as time taken during navigation is also less than previous methods.

1.4 Structure of the Dissertation

This chapter addresses the problem related to Mobile Robotics division as well as explore the investigation made to clear the objectives related to autonomous mobile robotics. In addition, the problem has been addressed in section wise, such as navigation system, trajectory planning, localization and kinematics strategies. By exploring the combined design of both algorithm i.e. for (i) navigation and localization and (ii) the sensor network, an effective navigational control system is designed. To provide more clarity about this thesis, later; the main aspects are described with different chapters (eight chapters), and fact that, logically each chapter is closely related to the each other.

- In Chapter 2, we present previous work related to navigation and path planning, kinematics analysis, fuzzy logic controller, recurrent neural controller, sensor integration and fusion of mobile robot.

- In Chapter 3, we assess the kinematics configuration of mobile robots, since it play an important role towards safe navigational design. After pointing the robust and feeble points of kinematic modelling, we clarify how an expected trajectory can be obtained using kinematic stagnation during navigation.

- Chapter 4 states the perception of the fuzzy logic, control design and summaries the methodology used to design an intelligent rule based fuzzy logic controller, which enables the mobile robot to navigate successfully in real world environment.

- Chapter 5 aims at the study of type 2 fuzzy logic, an enhancement of fuzzy logic behaviour, that will allow the formation of a better and certain path by getting rid of excess uncertainties.

- In Chapter 6 recurrent neural network technique being used for navigation of mobile robots is discussed.

- Chapter 7 describes hardware aspect of a simple mobile robot configuration by accumulating different sub modules.

- In Chapter 8 a detailed report of experimental results and discussion has been given. This chapter summarises the findings of all chapters discussed above.

- Finally in Chapter 9 conclusions of this research and future directions for further investigation has been discussed.

The papers published related to the thesis have been listed at the last.

Chapter 2

LITERATURE REVIEW

With the advent of modern technical era, researcher have conducted significant research related to the mobile robotics. Scientists categorise them based on their applications (i.e. indoor and outdoor applications). Presently principal structure of the review process is to analyse the findings till date related to the current research. We ensure that, each area and topic related to robotics contain much of data (catalogue is too long) and it cant be explain by single article. The objective of mobile robotic research is to study the robot with amazing knowledgeable capability by which robot achieve robust navigation in an known environment. Here the robot uses online sensors fusion as well as integration. This chapter provides detail survey report with important aspect of what the researcher are advancing in the area of navigational path analysis, control techniques as well as how to design mobile robot using different techniques.

2.1 Introduction

Researches related to previous mechanisms with autonomous mobile robot as well as issues related to autonomous control situations; section particularized two leading computational concerns. First one is path planning and following (Navigation) or second one is modeling of mobile robot and motion planning based on localization technique. Later, modelling of mobile robots involves deep analysis of kinematic and dynamic constraints in which navigation is the most essential part and it can be considered as a process. Based upon inputs, it covers specific knowledge of the environmental data i.e. description of the current position, destination and the agent's observations as well as output is the appropriate movement in orders to reach the destination position with avoiding obstacles and other exception situations that can arise.

After reviewing it is found the present position of research associated with mobile robotics mostly covers the problems related to navigation technique, control approaches and path finding technologies. Many, researchers have also suggested different types of techniques to extract solution from these problems. The current research on robotics deals with one of the major trends related to the development of robot navigational system for real world environment. To determine the position of the robot simultaneously with respect to the navigation is one of the perpetual problems related to robotics science [2]. In addition, there are large amount of uncertainties which appear on natural world at the time of robot motion (for unknown environment), creates another type of major problem [3].

Since, robotics has many unsolved problems, which synchronous when researchers design navigational system of autonomous mobile robot. Using mathematical formulations (related to motion geometry) and perceptional views as well combination of both at same time, suitable algorithm for navigation can be developed. For navigation purpose, this includes several discrete sensory inputs and output data. Consequently, on the basis of thousands of incoming signals from input sensory data elementary decisions has been made like turn left, turn right and stop [4–7]. In addition, this section includes collection of research articles based on mechanical modelling and provides theoretical documentation with kinematics control structure at the presence of sensory information.

2.2 Navigation of Mobile Robots

The process of determining as well as maintaining a trajectory balanced followed by target location in environment known as navigation [6]. Most of the robotics systems characteristically deal with different degrees of knowledge related to navigation. Researchers associated with mobile robotics have always faced problem with navigation systems (i.e. smother, faster movement and falling of humanoids robot) of the mobile robot. As a result, navigation system of the mobile robot is the more stimulating area of research. To develop a suitable, realistic and sensible navigation algorithm for autonomous mobile robot has been massive challenge for researchers. This is due to boundless potential applications of mobile robot inside indoor space (i.e. for industrial purpose and for military etc.) as well as in outdoor space (for space science research).

Based on the literature review, it is obligatory to first understand difficulties associated with mobile robot navigation system. The progress stated in past and recent with kinematics and dynamic modelling of robot based on intelligent navigational control design techniques is briefly described in this section. So this work is focused to solve particular problems linked with navigation, either direct (i.e. imperfection in mechanical design of the body) or indirect (i.e. path planning based on sensor integration, or with control structure algorithms).

Biological navigation activities have been important source of stimulation for robotics science. According to Leonard and Durrant-Whyte [8],the general problem of mobile robot navigation analysed by three questions, i.e. "Where am I", "Where am I going" and "How do I get there". Yet, the stage of biological system navigation occurrence; they usually work on a "how do I reach the target?" basis. Most of these systems have been dealt with different degree of knowledge depending upon the condition of environment.
Following are the broad classification of navigation system:

- Indoor Navigations
- Outdoor Navigations

DeSouza and Kak [9] presented paper on Vision for mobile robot navigation: this paper covers the developments of the last 20 years in the area of vision for mobile robot navigation. Major components of the paper deal with both indoor navigation and outdoor navigation.

2.2.1 Indoor Navigation

In the indoor navigation position of the robot, obstacles condition, path and goal position are known. To execute possible moion in the environment mobile robot combined all these known information and generate a navigational map [10]. In other words for indoor navigation the environment condition and robot path both are already configured inside robot brain by means of an algorithms for execution of work. Based on indoor navigation of mobile robot investigation has been made by researcher mainly related to navigation in flexible and robust manner. Related works for indoor navigation has been given in the next paragraph. Vision based navigation of a mobile robot may work with steps given in Fig. 2.1.

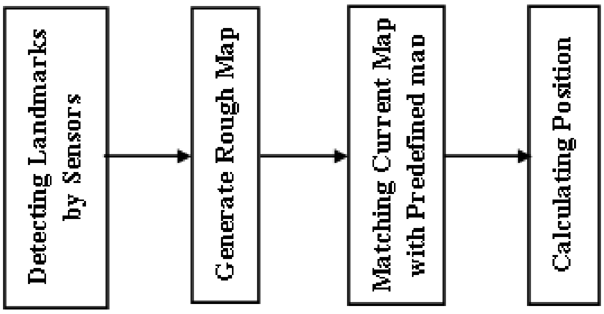


Figure 2.1: Indicates the complete cycle of vision based navigation

Courbon et al. has suggested work [11] for indoor navigation of mobile robot based on visual memory. The work for indoor navigation of wheeled mobile robot [12] suggested by Popa et al. explains how to achieve robot navigation with combination of sensors (i.e. temperature, proximity); web camera and odometer connected by PC through wireless system as well as indicated the power level.

Frank [13] has described localization and navigation techniques for indoor wheeled mobile robot.

Indoor navigation mainly categorized as:

- Map-Based Navigation
- Map Building-Based Navigation
- Map Less Navigation

Map-Based Navigation: Map-Based Navigation related to known system map navigation, at which topological map or user created map is predefined according to environment or data inside environment. In this method, online sensory part (mounted on the robot body) obtains raw data from its environment and through sensor fusion as well as sensor integration creates online map. After that, this map with user defined map or topological map for navigation is compared with the data from the sensors [9, 14, 15]. If the sensor-based map matches with the predefined map, then the vehicle derives its path towards its goal and estimate self-location in future [16, 17].

Map-Building-Based Navigation: In MBBN technique, overall topological navigation map based on online sensory data collected from environment at running time as well as

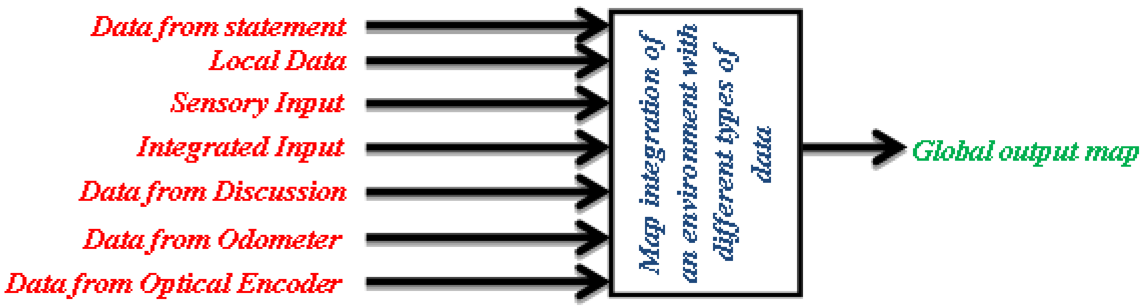


Figure 2.2: Schematic diagram of Global Map planning

sensor integration play an important role to construct final working map and based on this map execute navigation towards target [16, 18–21].

Map less Navigation: Map less navigation is performed by robot without any prior description of an environment, as well as neither Cartesian nor topological map is required for navigation, but navigation is totally based on set of online sensory based motor command. The robot can navigate by observing and extracting relevant information about the landmarks in the environment online [22, 23]. These elements can be objects such as desks, boxes and doorways. During navigation robot uses different processing unit and combined together to obtained clues for further navigation: the unit are listed in Fig.2.1. Accordingly, new project in the last few years uses vision systems navigation having map less navigation property [9, 22]. Finally result has been made; the map less navigation technique resembles human behaviour more than other approaches.

2.2.2 Outdoor Navigation

Autonomous navigation of a mobile robot in outdoor environment is one of the key issue in mobile robotics science. Further, localisation is other one and to obtain the different pose referred to as the most fundamental problem for researchers because, it sense and creates values of autonomous capability for mobile robot at real time navigation. For outdoor navigation, localisation is the problem of estimating robot's pose relative to its environment from sensory observation as well as it is the main necessity for successful mobile robot system control. Accordingly, in few years, there have been tremendous progress recorded for navigation system of mobile robot; mainly for outdoor environment as well as on the street for autonomous car [24].

Due to large outdoor environment configuration for car navigation proximity sensors such as the laser range finders (LRF) is commonly used for estimation of robot heading [25]. In addition, with the introduction of Velodyne (provides dense and extended proximity) [26] large range travel on the road is now possible. In case of outdoor navigation it provides clear appearance information that gives robust navigation to the car. Another approach for heading estimation and localization is through the use of teach-and-replay paradigms [27,28]. In this view, the robot is first manually steered through a specific route (in case of planned environment) during the teaching stage, and is than executed the same route during autonomous operation. This type of navigation having control strategy for mobile platform covers the range from tele-operated (real time guided by remote human operator in environment) to autonomous (robot takes its own decision through online sensors and processors) [29,30].

In order to carry out autonomous navigation tasks in an obstructed environment when stationary and moving obstacles co-exist, a mobile robot must be able to detect uncertainty in real time [31]. For detection of real time uncertainty it uses different elements such as GPS system, LRF sensor and AI methods or combination of all these elements [32–36]. Finally, the online obstacle avoidance task can be more accomplished under unknown and obstructed environment by integrating the information returned from various sensory (or sensor integration) at the time of real time outdoor navigation.

According to their level of strategies outdoor navigation may be divided into two directories i.e.:

- Planned Environments
- Amorphous Environments

Planned environment: Tsugawa et al. [37] introduced research report on structured environment i.e. "An automobile with artificial intelligence". In this research, he relied mostly on obstacle avoidance. Another approach has been made on this field i.e. laser-based classification approach for navigation [38]. Especially, this project suited for detecting low vegetation (grass surface); typically found in planned outdoor environments such as parks or campus sites. Further, researchers uses GPS and IMU based extended Kalman filter system [39] for advanced navigation through sensor fusion algorithm and suggested algorithm is applied to the advertising robot platform which is functioning well during 80 days in the real semi-outdoor structured environment. Planned environments required some form of clue related to navigating platform such as company, plant and stadium road information [40].

Amorphous environment: Outdoor navigation for ground vehicles in an environment is the most difficult tasks for researcher. The following steps are to carried out for outdoor navigation.

- Robot mapping the surface with its vision system
- Computing safe and unsafe areas on the surface within that field of vision based on any AI Technique
- Computing efficient path across the safe area, towards the desired destination
- Driving itself along the calculated path
- Repeating this cycle until either the destination is reached

The research articles related to outdoor navigation presented by Krotkov et al. [41] is based on sensor vision system as well as use generic characteristics for obstacle detection and covers amorphous environment with no regular property. Chen et al. [42] have been suggested pure reactive-based approach for outdoor navigation. Another research conducted by Ashoka et al. [43] for Robot localization with multiple sensors using interval analysis deals with the robot localization problem in a nonlinear and global way. Christian et al. [44, 45] presented his research article based on outdoor navigation for pedestrian environment using vision-based road recognition. Pedestrian environments poses a different challenge due to more availability of human that create new environmental condition time to time for mobile robot. In addition, pedestrian roads are much regulated than the one driven by car. Based on cognitive-merged statistical pattern recognition method, digital image processing has been used for autonomous navigation [46].

2.3 Kinematics of Mobile Robot

The kinematic model of a mobile robot contain principally the explanation of the allowable instantaneous motions with respect to its constraints. These patterns can be articulated in ordained form which is suitable for design of planning and control techniques. This section arrange detailed report of kinematics of mobile robotics system. The unicycle kinematics; reviews some of the control approaches for trajectory tracking and position equilibrium in an environment free of obstacles. Study of kinematic system is the first step on the way to achieving desired navigation related goals.

In addition, wheeled mobile robots (WMR) can't stand or deliver tasks (operate) in precious form without exact kinematics outlay. This section familiarises with work description related to structural parts of the robot without considering the mass and forces as well as enables the safe and accurate control structure. The plans which govern the system and relationship between control constraints as well as behaviour of a system in state space is well defend by kinematics modelling. Whenever designing of WMR are proposed, the control algorithm with all the assumptions of ideal WMR are taken into account. Validation and accurateness of control algorithm for WMR depend upon maximum creation related to model of the WMR. Precious path planning, localization modules and feasible direction of instantaneous motion depend upon architecture of kinematic model.

Mobile robots are more effective than treaded robots on solid, smooth surfaces, and will hypothetically be the first choice related to application in industry, due to solid, smooth plant surfaces in current industrial environments [47]. Additionally, quite a few mobility alignments can be found in the applications as stated above by Jones et al. [48]. The most common for single-body robots are differential drive and synchro drive tricycle or car-like drive, and omnidirectional steering [49]. Away from the significance of its applications, the problem related to autonomically path planning and control structure of mobile robot has involved the attention of researchers in sight of its theoretical challenges [50]. To control the motion of wheeled mobile robot, researches drawn substantial attention over the past few years. The nonholonomic behaviour with robotic systems is typically stimulating, because it indicates that, the mechanism can be totally controlled with a restrained number of actuators. Notably, these systems are a typical example of nonholonomic devices due to the perfect rolling constraints on the wheel motion [51]. In addition, to control the mobile robot in an environment study of position equilibrium with trajectory tracking is essential.

The aim of position equilibrium is to stabilize the robot to a locus point, whereas the aim of trajectory tracking is to have the robot follow a reference trajectory. For mobile robots trajectory tracking is simple to attain, than position equilibrium [52]. The motion-planning and control includes discovery of continuous track or trajectory respectively, from initial point to the termination point and also avoids obstacles in efficient manner. The feedback equilibrium at a given position cannot be attained through smooth time-invariant control [53]. This labels that the problem is truly nonlinear; linear control is ineffective, even locally, and innovative design techniques are needed. An ideal automatic driving control system should be able to comply with changes in slip conditions so as to optimise the control performance.

Trajectory tracking is more natural for mobile robots. Generally, the reference trajectory is attained by means of reference robot; hence, all the kinematic constraints are indirectly considered by the reference trajectory [54]. Gracia and Tornero [55] proposed kinematics control work applicable for any type of WMR. In this paper stability of a general class of mobile robot along with path-tracking algorithms have been studied. The delay problem can be resolved openly using the transcendental characteristic equation that appears when the time delay is measured. This is valid for straight paths and paths of constant curvature [56]. The autonomous navigation of wheeled robots needs integrated kinematic control to execute trajectory tracking, path following and stabilization. The coupling effect between linear and angular motion is considered in the fuzzy steering by building appropriate linguistic rules [57]. A fuzzy logic approach can be used in order to minimise the position and orientation errors caused by odometric problems.

The problem of terrain acquisition presents a special case of robot motion planning. The harmonic drive system for non-linear controller to compensate for kinematic error in the presence of flexibility in high-speed regulation and trajectory tracking application has been proposed by Gandhi and Ghorbel [58]. In it, a robot that operates in an unfamiliar scene populated with a finite number of objects of unknown shapes and dimensions is asked to cover the scene and build its complete map using some sort of sensory feedback and generating as short a path during operation as possible [59]. The behaviour of space robots with torque and attitude controller has been discussed by Pathak et al. [60]. A receding horizon controller may be used for tracking control of wheeled mobile robots subject to nonholonomic constraint in the environments without obstacles. The control policy is derived from the optimization of a quadratic cost function, which penalizes the tracking error and control variables in each sampling time [61]. This methods, improve the domain of applicability of a wide range of obstacle avoidance methods [62]. Basically, both trajectory tracking and posture stabilization controllers can be implemented with on-board computing power.

The wheels of mobile robot have been modelled as a torus by Chakraborty and Ghosal [63] and used as a passive joint thereby enforcing a lateral degree of freedom so as to get a slip free motion in an uneven terrain without using variable length axle (VLA) as it has several limitations in application. Zhang et al. [64] have developed a feedback control law [7, 65], allowing a 2-wheel differentially driven mobile robot to track a prescribed trajectory by using the integral backstepping method and Lyapunov function for ensuring a trajectory tracking controller with global asymptotic stability.

Zohar et al. [66] recently proposes control schemes for trajectory tracking of mobile robot model which includes kinematic and dynamic effects on motion by using the notion of virtual vehicle [67] and the concept of flatness [68], and applying the backstepping [69] methodology.

Gandhi and Ghorbel [58] have proposed the harmonic drive system for non-linear controller to compensate for kinematic error in the presence of flexibility in high-speed regulation and trajectory tracking application. A single curvature trajectory, having a constant and large rotation radius, has been proposed by Han et al. [70] as an optimal trajectory, in order to minimize the tracking error of the differential drive mobile robot while capturing a moving object along with the pre-determined initial and final states. A receding horizon controller may be used for tracking control of wheeled mobile robots subject to nonholonomic constraint in the environments without obstacles. The control policy is derived from the optimization of a quadratic cost function, which penalizes the tracking error and control variables in each sampling time [71, 72].

2.4 Fuzzy Logic Methodology

Choi et al. [73] solved the navigation problem in a simple way. He has described whenever a robot challenges large, non-convex or dispersed obstacles as well as to find appropriate local minimum points within this area, always difficulties appear. Accordingly, he suggested algorithm, which covers two layer hierarchical systems to solve the problem and provide the name of the layer as, lower layer for avoiding or approaching and upper layer to combine this logic. Silva et al. [74] has proposed work for navigation of mobile robot using fuzzy logic. In this paper researchers describe how a robot uses its local information to control the steering and velocity while moving inside unknown environment. The proposed method is direct and effective and uses sensory data in order to design the fuzzy logic controller. Park and Zhang [75] developed behavior based dual fuzzy approach to navigate the mobile robot in unknown environment. Eight ultrasonic sensors, a GPS sensor and two fuzzy logic controllers with separate '81' rules were used to realize this navigation system. Here two fuzzy control algorithms is used one for navigation and other for avoiding obstacle and edge detection. Qian and Song [76] have presented a research article based on sonar ring and its implementation for autonomous navigation. The local trap problem describe in this paper and uses sonar sensor to obtain the environmental information.

Pioneer 3DX robot is used for experiment and FSM (finite state machine) method implies transfer the navigation status of mobile robot when environmental information is changed. Carrillo et al. [77] developed navigation system for mobile robots based on different patterns of behavior. In this work, a layered approach is employed, in which a supervision layer based on the context which makes a decision that behavior to process, rather than processing all behaviors. Sharma et al. [78] have suggested work related to harmony search based adaptive fuzzy tracking controllers for vision-based navigation. This is hybrid optimization approach, which combined harmony and Lyapunov theory for vision based control. It is utilized to design two self-adaptive fuzzy controllers, for x-direction and y-direction movements of a mobile robot. Parhi [7] has proposed navigation control using fuzzy logic and a Petri Net model is used to develop the control structure. This approach is suggested for cluster environment where numbers of robots are moving and one robot detects another robot as dynamic obstacle and follows the avoiding rule. Pradhan et al. [79] have presented a hybrid method for navigation of multiple mobile robots in unknown environment using neuro-fuzzy approach and used an image sensory to detect the uncertainty in environment. With four inputs as Gaussian membership functions has been trained in a network, which provides two outputs. Kim et al. [80] have developed an autonomous multi-mobile robot simulator and the approach is based on a potential field method and fuzzy logic system. In this paper, each robot independently selects its destination and considers other robots as dynamic obstacles, and there is no need to predict the motion of obstacles.

2.5 Type 2 Fuzzy Logic

Type-2 sets can be used to convey the uncertainties in membership functions of type-1 sets, due to the dependence of the membership functions on available linguistic and numerical information [81]. Linguistic information (e.g., rules from experts), in general, does not give any information about the shapes of the membership functions. When membership functions are determined or tuned based on numerical data, the uncertainty in the numerical data, e.g., noise, translates into uncertainty in the membership functions. In all such cases, information about the linguistic = numerical uncertainty can be incorporated in the type-2 framework. In [82], Liang and Mendel have demonstrated (using real data) that a type-2 fuzzy set, a Gaussian with fixed mean and uncertain standard deviation (std), is more appropriate to model the frame sizes of I=P=B frames in MPEG VBR video trac than is a type-1 Gaussian membership function. When the secondary MFs are interval sets, we call them "interval type-2 fuzzy sets". The operations of interval type-2 fuzzy sets are studied in [83, 84].

Fuzzy sets have been around for nearly 40 years and have found many applications. However they suffer from certain problems [85]. These fuzzy sets are, in fact, type-1 fuzzy sets. Type-2 fuzzy sets are 'fuzzy fuzzy' sets and are more expressive [86]. Type-2 fuzzy sets and systems generalize (type-1) fuzzy sets and systems so that more uncertainty can be handled. From the very beginning of fuzzy sets, criticism was made about the fact that the membership function of a type-1 fuzzy set has no uncertainty associated with it, something that seems to contradict the word fuzzy, since that word has the connotation of lots of uncertainty.

To go from an interval type-2 fuzzy set to a number two steps are required. The first step, called type-reduction, is where an interval type-2 fuzzy set is reduced to an intervalvalued type-1 fuzzy set. There are as many type-reduction methods. An algorithm known as the KM Algorithm is used for type-reduction. Although this algorithm is iterative, it is very fast. The second step of Output Processing, which occurs after type-reduction, is called defuzzification. Because a type-reduced set of an interval type-2 fuzzy set is always a finite interval of numbers, the defuzzified value is just the average of the two end-points of this interval.

Hagras [87] proposed his work based on hierarchical Type-2 fuzzy logic control architecture for autonomous navigation of mobile robot on changing and dynamic unstructured environments. In this paper researcher presented a novel reactive control architecture for autonomous mobile robots that is based on type-2 FLC in a hierarchical form. Baklouti and Alimi [88] presented paper, design of interval Type-2 TSK fuzzy logic controller for motion planning of mobile robot in dynamic and unknown environment. Nurmaini and Hashim design [89] an embedded fuzzy Type-2 controller based on eight ultrasonic sensor distance behavior, for mobile robot navigation. In this paper describes inputs are depends upon mounted ultrasonic sensors and sent to a microchip PIC 16F84 microcontroller onboard the robot. Furthermore the PIC16F84 analyses the inputs as data and provides the necessary control signal. Again, Nurmaini et al. [90] proposed work for navigation of mobile robot using RAM-Network Based type-2 fuzzy neural method for real time environment. The suggested architecture can be implemented easily with low cost range sensor and low cost microprocessor. To minimize the execution time used a look-up table and that output stored into the robot RAM memory and becomes the current controller that drives the robot. Chen and Yao [91] have presented paper based on Type-2 fuzzy control for automatic guided vehicle that has wall-following behavior. In this work, an interval type-2 fuzzy wall-following controller (IT2FWFC) is developed to improve the resilience to inaccuracies that can hinder the normal operation of an AGV. In order to reduce computational loads during practical control, a simplified center-of-sets (COS) type-reduction procedure with clearly marked rule indices is also developed. Junratanasiri et al. [92] presented research article concerning navigation system of mobile robot based on type-2 fuzzy methodology for uncertain environment and develop path planning algorithm, which avoid static and dynamic both obstacle type inside working environment. In this work fuzzy vector method has been proposed and mainly research concerning with dynamic type of obstacle which movement recorded globally in nature. Linda and Manic [93] proposed research work for autonomous navigation and develop the methodology which useful for detecting dynamic obstacle in uncertain environment. This work is based on interval type-2 fuzzy logic system. To track the uncertainty modeling throughout the inference process, two novel uncertainty quantifiers are proposed: first one is antecedent uncertainty and the second one consequent uncertainty quantifier's. Mbede et al. [94] presented research which concern slices based type-2 fuzzy methodology for motion control of autonomous Robotino mobile robot. In addition, combine the advantage of more controllable degrees of freedom offers by Omni-directional to develop the motion algorithm for Robotino omni directional robot. This work based on real time local path modification and motion planning system using the concept of Slices based general type-2 fuzzy sets to allow ROMR facing of high levels uncertainties encounters in changing and dynamics unstructured indoor environments.

2.6 Recurrent Neural Network

Requirements related to control unit of mobile robot is the essential concern and which is the reason; navigation and path planning studied extensively. To generate online map for path planning sensors network has been used widely. Hence, robot move from one pose to another and avoid obstacles on run time in effective manner. In addition, to conduct autonomous navigation on ambiguous environment, where stationary and moving obstacles (human, robots) co-exist, a mobile robot must be able to detect uncertainty at real time [95, 96]. The robot system employed with wheel encoders, sensor network, odometers and camera to detect nearby obstacles. This chapter provides simply review related to recurrent neural network (RNN) based learning methodology.

RNN approach [97–99] has been extensively used in recent year, if integrated map learning (integration of sensory) required. During the navigation, current position of the robot can be known continuously from sensor fusion, odometry and camera readings. During navigation, the mobile robot is continuing with significant navigation errors, which can be made due to equipment readings; accordingly, estimated location is far from the actual one. Therefore, switching between local and global frames is employed for a calibration purpose after odometry errors are accumulated. This methodology offers two advantages compare to other method. Primarily, the gathered odometry errors can be balance and precious navigation may be achieved. Secondly, if sensor fusion is not achieved, at that time robot navigation remain without a disturbance under the calibrated local coordinate frame for a short distance.

In particular, recurrent neural network RNN is a dynamic part of neural network, which involves both methodology feed forward and feedback connections [100,101]. RNN mainly used for optimize the control problem. Recently many robotics projects cover RNN to develop suitable control systems and optimize the navigation map [102, 103]. Further, localization problem related to mobile robot is the estimation of robot's location and orientation comparative to its environment. In addition, it is the major problem related to mobile robotics science as well as it plays principle role for much successful navigation. Moreover, to develop the control algorithms, which has ability to create collision free path (to follow obstacle avoidance behavior) [104–106]; is the module of advanced robotics control systems.

For RNN composition one feedback and feedforward connection is essential and recurrent neural network (RNN) has ability to approach any constant purposes closely. On the other hand, the feedback RNN is based on static mapping. Even if several research has used the feedback RNN to communicate with dynamical problems, the feedback RNN needs a large number of neurons to denote dynamical responses through time domain.

According to Haibo et al. [107] recurrent neural network are practical to the forward modeling of the sensory-motor flow of a miniature mobile robot. It offered that the robot is capable to calculate the sensory signals a few steps ahead, which suits for simple environment. Du et al. [108] proposed work for mobile robot behavior controller based on genetic algorithm (GA) and diagonal recurrent neural network (DRNN). This method contain advantages of time series estimation capability due to its memory nodes, as well as local recurrent and self- feedback connections. Wai et al. [109] presented research article related to control of mobile robot, which has ability to map robust path and deliver target tracking control architecture to the mobile robot through dynamic petri recurrent fuzzy neural network. In this article, an adaptive moving-target tracking control (AMTC) structure via a dynamic Petri recurrent fuzzy neural network (DPRFNN) is created for a vision-based mobile robot through incline camera. In this DPRFNN, the idea of a Petri net (PN) and the recurrent frame of internal feedback loops are combined with traditional fuzzy neural network (FNN) to improve the computation weight of parameter learning and to develop the dynamic mapping of network capability.

2.7 Sensor Fusion and Integration

To integrate the signals from multiple sources, sensor fusion is the desired creation, which allow to extract data from different sources and integrate them into single signal or data. The data received from multiple sensors is recognized using data fusion algorithms. Accordingly, fusion algorithms are classified based on working creation such as fusion based on probabilistic models, fusion based on least-square technique and fusion based on intelligent theories. But the main creation is to implement the suitable AI techniques such as fuzzy logic, neural network and genetic algorithm (but not limited) inside the system according to sensory part for fusion consideration.

The sensor data integrated and fusion takes place over time to time, when mobile robot combined with suitable AI method and used for any engineering applications. For navigation of wheeled mobile robot requires large number of data from its sensory environment through sensor and these data can be used at the time of creation of environmental map. After collection of information from environment that is similar to the real data has to be integrated over time and converted into single meaningful signal or information that can be used by control system of mobile robot to plan its environmental path. Some of the research articles used Kalman filter method to integrate the signals or information receives from multiple sources of sensing parts. Sasiadek and Khe have presented paper [110], which delivered the knowledge how to sensor fusion helps to improve the control structure and methodology used for fusion based on combination of AI technique (fuzzy) with Kalman filter for guidance, navigation, and control of mobile robot. This paper demonstrate the performances of Kalman filter and fuzzy Kalman filter for position approximation application under different circumstance. Xu et al. [111] have present work with extended Kalman Filter based magnetic guidance for intelligent vehicles. This paper, suggested a magnetic guidance system for intelligent vehicle based on EKF (Extended Kalman Filter), which fuses magnetic sensors with encoders. The thirteen Anisotropic Magneto Resistive (AMR) sensors are used instead of Hall-effect sensors in the projected magnetic sensing structure due to their high sensitivity with low cost as well as an EKF is applied to remove

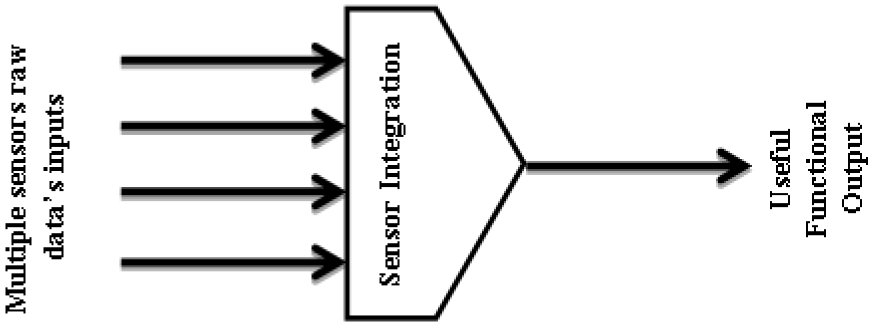


Figure 2.3: Functional diagram of sensor integration

the cumulative error with the dead-reckoning method.

Luo and Kay have presented research work on multisensory integration and fusion for intelligent system. The control of an intelligent system such as battlefield management, mobile robot navigation, multitarget tracking, and aircraft navigation without human operator requires some intelligent element (like sensors) with intelligent technique [112] and it is the base to use multisensory integration and fusion [113]. Another approach is made [114], i.e. navigation and localization based on grid mapping system through sensor integration, at which all sensor data combined together to form grid map and involves learning Bayesian network [115, 116] for navigation. Martin et al. in 2006 presented his work related to multi sensor fusion through network using a probabilistic aggregation scheme for people detection and tracking of an object. Through this paper, Martin [117] introduce integration of several sensor modalities and also present a multi-modal, probability-based people detection and tracking system and its application using the different sensory systems of mobile interaction robots. Koshizen [118] introduced research article, which deliver the knowledge i.e. how to improved sensor selection technique by integrating sensor fusion for estimation of robot position. This research provides the information about the localization and navigation of mobile robot through modelling and reducing the environmental uncertainty. For modelling and reducing the uncertainty; Gaussian Mixture of Bayes with Regularised Expectation Maximisation (GMB-REM) method has been employed. Persson et al. [119] proposed the work related to fusion of aerial images and sensor data from a ground vehicle to improve semantic mapping. This paper deliberates how aerial images can be used to spread the observation array of a mobile robot. The method can speed up exploration or planning in areas not yet visited by the robot. The principal objective of this work is to develop a methodology which accommodates the use of multiple heterogeneous sensors for robotic applications, without being restricted to a particular sensor configuration, but aspiring to the theme of multiple mutually supportive sensors, operating synergistically to achieve a common objective.

Research proposed by Neto et al. [120]; presents an algorithm for localization of robot based on the complementary filtering methodology to guess the localization and orientation, through data fusion from IMU, GPS and compass. The main advantages of this algorithm is to reduce the complexity of implementation and provide high quality of the results for the navigation event in uneven terrain. Jin et al. [121] proposed work related to space and time sensor fusion for mobile robot navigation. The proposed work is based on sensor-fusion technique, where the data sets for earlier moments are accurately converted and fused into the current data sets and allow exact measurements, such as the distance from obstacle or the position of the robot. Kwon et al. [122] proposed his work for robot navigation based on stereo vision system through 3D visual maps of interior space with a new hierarchical sensor fusion architecture. The core part of this work is how the uncertainties are managed with interval based logic. This logic allows system to fuse information extracted from the sensors at different levels of abstraction.

2.8 Sensors for Mobile Robots

To plan the accurate navigation strategies for mobile robot inside known as well as unknown environment, researchers has been used different types of sensors to build online map for robot navigation. Accordingly, these sensors are classified into three modules i.e. *Ultrasonic Sensors, Infrared Sensors, and Other types of Sensors (combination of both or others)*.

Wu and Tsai [58] have verified that the grouping of three ultrasonic transmitters and two receivers can define both the position and the orientation (localization) of an autonomous mobile robot with respect to a reference frame individually. A technique for approximating the position and heading angle of a mobile robot moving on a plane surface has been proposed by Boem and Cho [84]. Their localization method utilizes two passive beacons and a single rotating ultrasonic sensor.

The sensible investigates [19, 93, 94] have involved ultrasonic sensorbased motion planning for mobile robot. They have used environmental data observe by sensor as input signal and plan its motion according to algorithm.

Kleeman and Kuc [123] have established theory based upon this theory, two transmitters and two receivers are necessary as well as sufficient for a mobile robot to decide the difference between planes, corners and edges inside environment. Ko et al. [124] have proposed a method to extract reality on landmarks for the indoor navigation of an autonomous mobile robot using a group of ultrasonic sensors. Hong and Kleeman [125] have deliberated the information about sensing of room boundaries for a mobile robot navigation using 3D sonar sensor. They have applied their algorithm with an Extended Kalman Filter (EKF) for motion planning.

Everett and Flynn [20] have labelled a programmable nearinfrared amplitude detection sensor for navigation in an unstructured environment. Yu and Malik [59] have presented research work to control the navigation of a mobile robot using an infrared sensor as well as avoid collision with obstacles. Another, related work have been proposed by Kube and Zhang [38]used infrared sensors for avoidance of obstacle. In this work, the range for detection of an obstacle through inferred sensors is given by 1.5 m during navigation. Related work have been also presented by Vandorpe et al. [53,54] for path planning as well as avoidance of an algorithm with group of infrared sensors. The advantage of infrared sensors over other sensors it gives a complete panoramic image of the environment.

Borenstein et al. [126] have discussed the navigation of a single mobile robot with various sensory techniques. They have shown that the magnetic compass is a very good sensor for determining the location and heading angle (x, y, and θ) for a mobile robot. However, the sensor is not appropriate for obstacle distance measurement. Their method is suitable for a single mobile robot navigating in an unknown environment.

2.9 Summary

This chapter covers a brief introduction of mobile robotics architecture that provides kinematics strength to the mobile robots as well as delivers trajectory details with artificial intelligence technique that helps to design an intelligent control algorithm.

This chapter has comprehensively reviewed the several characteristics related to mobile robotics science and the advancement made so far in the navigation system of mobile robot.

First the investigation on kinematics of differential drive mobile robot has been talked and further the problem related to position estimation, path following, and trajectory tracking have been confirmed. The principle for stable control algorithm; have capability to dealing with nonholonomic navigational problems. This chapter also delivers the detailed review of various researches in last decade. The working principle for navigation of mobile robot is using different intelligent controller such as Fuzzy Logic controller, Type 2 FLC, and Recurrent Neural Network Controller is outlined here. This provides powerful reasoning to the robot inside working environment and based on this robot differentiates between targets and surrounding obstacles. With reference to the analysis it has been observed that the mobile robot navigation can be organized successfully in a known as well as partially unknown environments using the above approaches.

Chapter 3

Kinematics Estimation

3.1 Kinematics Model of Mobile Robot

According to the number of researchers [14, 16, 21–23] kinematics is the study of motion without reference to mass or forces that causes the motion. In addition, it also concerned with problem such as predicting the position of an object in future against its initial position and velocities. Basically, the navigation of mobile robot is mainly concerned with position oriented programming, due to this study of kinematics is essential part in this research area. On another word it is the branch of classical mechanics that describe the geometry of motion of points, object and group of object without consideration of the causes of motion. In this section, the transformation between a coordinate frame (local reference plane) and ending frame (goal reference plane) is studied in detail. The transformation given here studies how to achieve the goal from local frame.The transformation is how to robot communicate with position and orientation. The accurate estimation of the current position of the robot throughout its travel in motion is area discussed here.

Kinematic is mainly divided into two types i.e. forward and reverse kinematics. Forward kinematics deals with the position, orientation and velocity of the end effector. This gives the displacement and joint angles. Similarly, reverse kinematics deals with the joint displacement and angles from the end effector concerning position and velocities. Kinematics mainly depends on homogeneous transformation.

3.1.1 Representation of position of mobile robot

In the Fig. 3.1 (X_R, Y_R) the robot moving frame,whereas (X_G, Y_G) is the static or global reference frame. Also consider that 'Q_G' represented the robot posture in the global co-

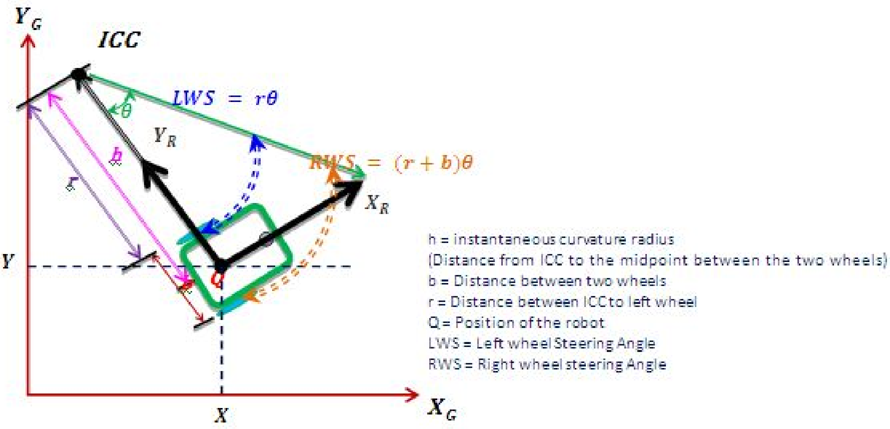


Figure 3.1: Kinematics Notation of the Robot World.

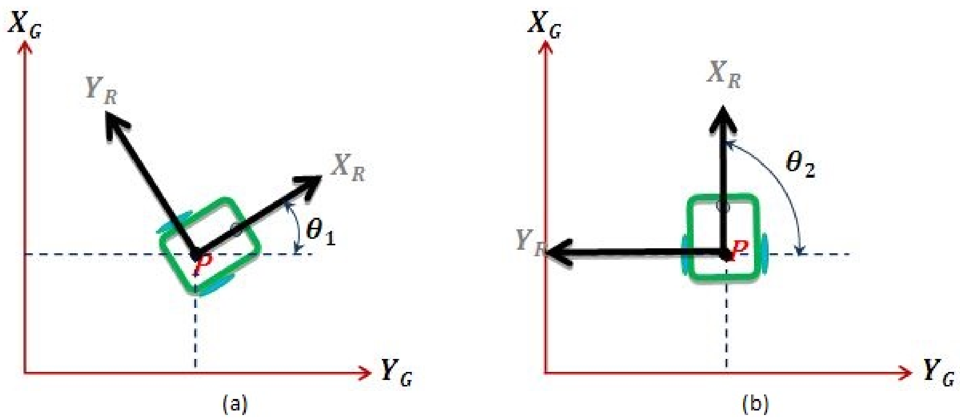


Figure 3.2: (a) Change in steering angle at Global and Local Reference Frame. (b) The mobile robot aligned with a global frame

ordinate and '$M(\theta)$' is the rotation matrix expressing the orientation of the base or global frame with respect to the robot or moving frame. In the Fig. 3.2 θ_1 (Fig. a)is changed to θ_2 (Fig. b) and describe the orientation of the robot.

$$(Robot\,posture)\,Q_G = \begin{bmatrix} X \\ Y \\ \theta \end{bmatrix} \tag{3.1}$$

Where,

(X, Y) = Position of the Robot.

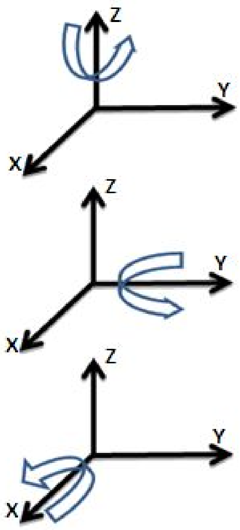


Figure 3.3: Representations of matrix.

θ = Orientation of the robot.

Now, Rotation Matrix is given by,

$$\mathrm{M}(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

The relation between the reference frames is indicated by Fig. 3.2 similarly, the equation for standard orthogonal rotation transformation is given by:

$$[\theta = \theta_2 - \theta_1] \tag{3.3}$$

The equation (defined above) can be used to access the robot motion in the global reference frame from motion in its local reference frame.

$$\dot{Q}_R = M(\theta)\,\dot{Q}_G = \begin{bmatrix} \dot{X} & \dot{Y} & \dot{\theta} \end{bmatrix} \tag{3.4}$$

Where, $\dot{Q}_G$ is the motion with respect to static frame and $\dot{Q}_R$ is the robot frame motion. For this 2D motion, rotation around z-axis (R_z) is only considered.

$$R_z(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.5}$$

$$R_Y(\sigma) = \begin{bmatrix} cos\sigma & 0 & -sin\sigma \\ 0 & 1 & 0 \\ sin\sigma & 0 & cos\sigma \end{bmatrix} \tag{3.6}$$

$R_y(\sigma)$ is the rotation around *y-axis* with an angle 'σ'

$$R_X(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \tag{3.7}$$

$R_x(\alpha)$ is the rotation around *x-axis* with an angle 'α'

Which phenomenon is represented by only one equation i.e.:

$$\dot{Q}_G^T = [\dot{X}\ \dot{Y}\ \dot{\theta}]^T \tag{3.8}$$

3.2 Velocity control of mobile robot

In case of two drive rolling wheel,

$W(t)$ = angular velocities of wheels

$V_r(t)$ = linear velocities of right wheel

$V_l(t)$ = linear velocities of left wheel

r = nominal radius of each wheel

R = instantaneous curvature radius of the robot trajectory, relative to the mid-point axis.

θ = angle of rotation

From Fig. 3.4, angular velocities of right wheel $W_r(t)$ with respect to time and angular velocities of left wheel $W_l(t)$ with respect to time is given by equation,

W(t) = linear velocities of the wheels ÷ (curvature radius of trajectory+length)

$$W_r(t) = V_r(t) \div \left(R + \frac{L}{2}\right) \tag{3.9}$$

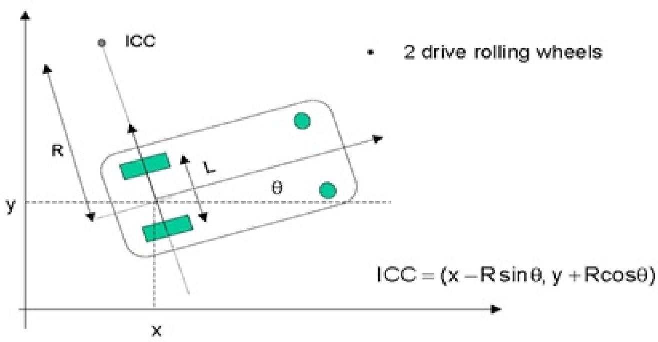


Figure 3.4: Steering control of mobile robot.

$$W_l(t) = V_l(t) \div \left(R - \frac{L}{2}\right) \tag{3.10}$$

Then velocity is given by:

$$\begin{bmatrix} V_x(t) \\ V_y(t) \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2} \\ 0 \\ \frac{r\dot{\varphi}_1}{2L} + \frac{-r\dot{\varphi}_2}{2L} \end{bmatrix} \begin{bmatrix} W_l(t) \\ W_r(t) \end{bmatrix} \tag{3.11}$$

Where,

$W_l(t)$ is the angular velocity of the left wheel and

$W_r(t)$ is the angular velocity of the right wheel.

$\dot{\varphi}_1$ and $\dot{\varphi}_2$ is the spinning speed of each wheel.

3.3 Analysis of wheel kinematics constraints

The kinematics constraint on a mobile robot comes from the combination of constraints from its wheel. Furthermore, motion of each individual wheel can be combined in order to find the motion of the robot as a whole. For this following assumption have been made for the analysis:

- ◇ The wheels are stable in nature and there is only one point contact between wheel and the surface.
- ◇ Wheel motion is pure rolling and follows to a null velocity at the contact point.

◇ The steering axes are orthogonal to plane surface of the ground.

◇ The wheels connection to the body or chassis is rigid in nature.

◇ During the motion, the plane of each wheel remains vertical and the wheel rotates around its axel, whose orientation with respect to the frame can be fixed or varying.

In this area, we have considered two constraints for each wheel type while the robot is in motion. The first constraint imposes the theory of pure rolling and the second one imposes the concept of no lateral slippage of the wheels in motion. Based on geometry wheels are classified into five types, i.e.:

- Conventional or fixed standard wheel
- Steered standard wheel
- Castor wheel
- Swedish wheel
- Spherical wheel

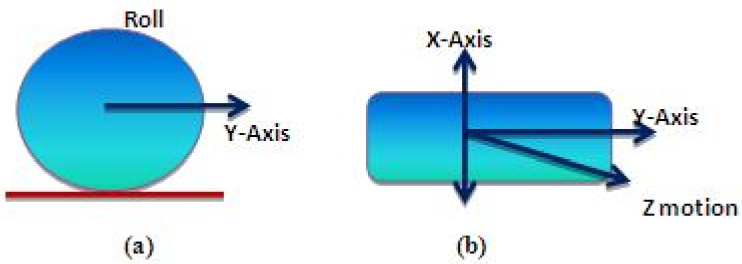


Figure 3.5: Wheel Kinematic Constraints (a) Pure Rolling and (b) Lateral Slip.

3.3.1 Fixed Standard wheel

Fixed standard wheel has no vertical axis of rotation, thus its angle to the robot chassis is fixed and therefore limited to have only backward and forward motion in the horizontal plane and rotation around its point of contact with the ground plane (from Fig. 3.5 to 3.7).

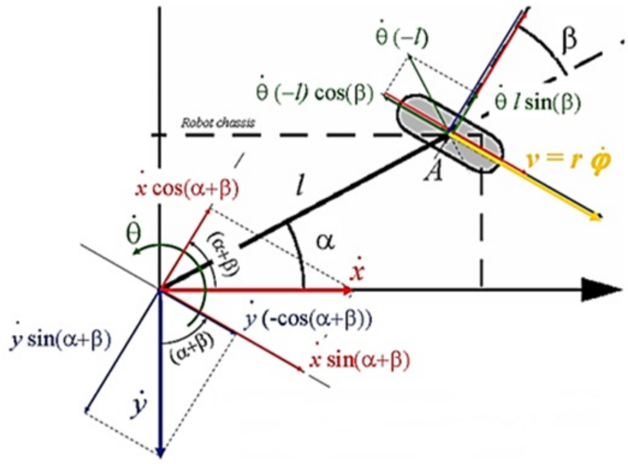


Figure 3.6: Fluctuation of velocity in all type of wheel.

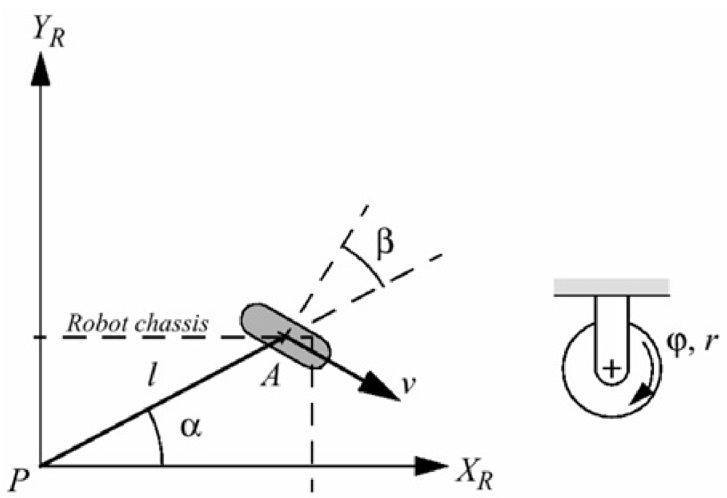


Figure 3.7: Fxed standard wheel.

For pure rolling [127] the equation is given below:

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-1)\cos\beta]\mathrm{M}(\theta)\dot{Q}_G - r\dot{\varphi} = 0 \tag{3.12}$$

Where, $M(\theta)\dot{Q}_G - r\dot{\varphi} = [\dot{X} \quad \dot{Y} \quad \dot{\theta}]$

The sliding constraint for this wheel enforces the wheel's motion normal to the wheel plane must be zero:

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-1)\cos\beta]\mathrm{M}(\theta)\dot{Q}_G = 0 \tag{3.13}$$

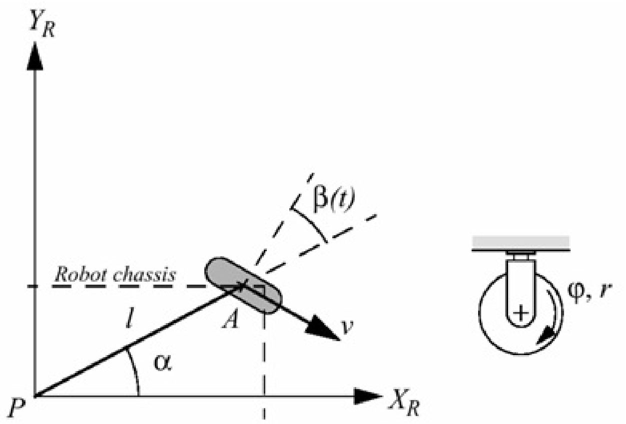


Figure 3.8: Steered standard wheel.

3.3.2 Steered Standard Wheel

Fig. 3.8 represents the steered standard wheel with its parameters. This type of wheel poses another DOF rather than fixed standard wheel as it spins around its vertical axis,so β changes to $\beta(t)$. The rolling and sliding constraints are:

Along the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-1)\cos\beta]\mathrm{M}(\theta)\dot{Q}_G - r\dot{\varphi} = 0 \tag{3.14}$$

Orthogonal to the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-1)\cos\beta]\mathrm{M}(\theta)\dot{Q}_G = 0 \tag{3.15}$$

3.3.3 Caster Wheel

It is similar to the steered standard wheel, but the only difference is, its axis of rotation is offset to the centre of the wheel and does not pass through the ground contact point. For this reason we have to introduce a new parameter that specify the position of the caster wheel and given by symbol 'd' (Fig. 3.9).

The rolling and sliding constraints are:

Along the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-l)\cos\beta]M(\theta)\dot{Q}_G - r\dot{\varphi} = 0 \tag{3.16}$$

Orthogonal to the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-l)\cos\beta]M(\theta)\dot{Q}_G + d\dot{\beta} = 0 \tag{3.17}$$

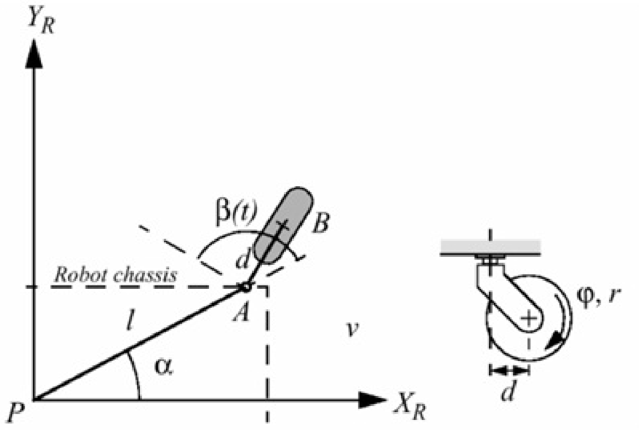


Figure 3.9: Caster wheel.

3.3.4 Swedish Wheel

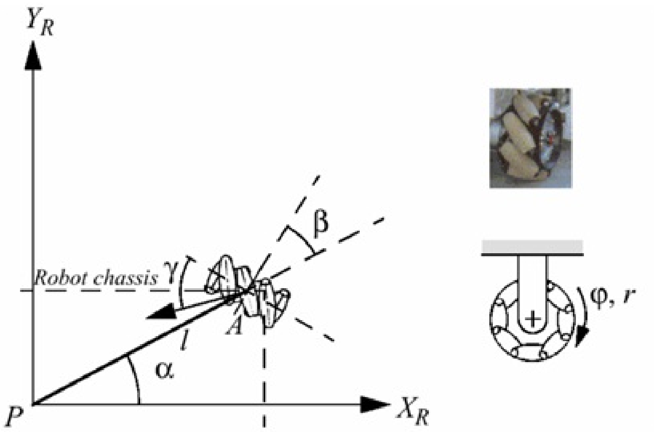


Figure 3.10: Swedish wheel.

It is also called as ‘Omni’ wheel, similar to ‘Mecanum’ wheel. This wheel has small discs around the circumference which are perpendicular to the rolling direction (Fig. 3.10). The effect is that the wheel will roll with full force, but will also slide laterally. These wheels are often employed in holonomic drive system. It consists of at least three rollers whose axes are tangent to the wheel perimeter and free about rotation. Swedish wheel can be designed similar to a fixed standard wheel with rollers connected to the wheel perimeter with axis that are anti parallel to the main axis of the fixed wheel component. The rolling and sliding constraint are:

Along the wheel plane

$$[\sin(\alpha+\beta+\sigma) - \cos(\alpha+\beta+\sigma)\,(-l)\cos(\beta+\sigma)]M(\theta)\,\dot{Q}_b - r\dot{\varphi}\cos\sigma = 0 \qquad (3.18)$$

Orthogonal to the wheel plane

$$[\sin(\alpha+\beta+\sigma) - \cos(\alpha+\beta+\sigma)(-l)\cos(\beta+\sigma)]M(\theta)\dot{Q}_G - r\dot{\varphi}\sin\sigma - r_{sw}\dot{\varphi}_{sw} = 0 \quad (3.19)$$

3.3.5 Spherical Wheel

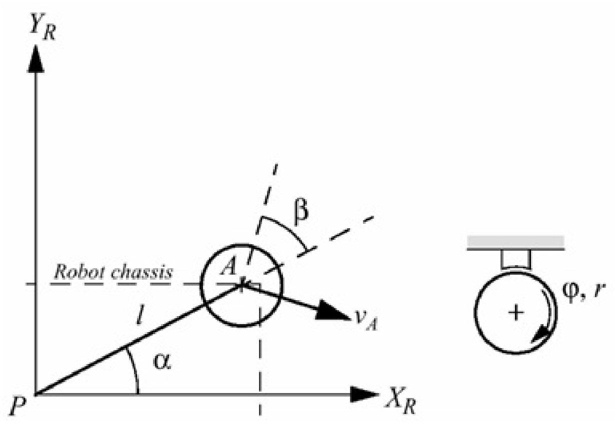


Figure 3.11: Spherical wheel.

Spherical wheel (Fig. 3.11) is omnidirectional and imposes no constraint on the robot chassis kinematics. Therefore equation simply describes the roll rate of the ball in the direction of motion V_A of point 'A' on the robot.

Along the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)(-l)\cos\beta]M(\theta)\dot{Q}_G - r\dot{\varphi} = 0 \quad (3.20)$$

Orthogonal to the wheel plane

$$[\sin(\alpha+\beta) - \cos(\alpha+\beta)\,l\sin\beta]M(\theta)\dot{Q}_G = 0 \quad (3.21)$$

3.4 Robot Kinematic Constraints

The study of robot kinematic constraints is associated with only fixed and steerable standard wheels.The equations of previous section, describe caster, Swedish, and spherical wheel,which imposes no kinematic constraints with robot chassis. Since, $\dot{Q}_G$ can range freely in all of these cases, owing to the internal wheel degree of freedom. Here, the robot is considered to have a total 'N' number of standard wheels, some of them are fixed wheel, steerable standard wheel, caster wheel, Swedish wheel, and spherical wheel. From Fig. 3.7

'β_f' refer to the orientation of the fixed standard wheel (N_f) and $\beta_s(t)$ refer to the variable steering angle (from Fig. 3.8) of steerable standard wheel (N_s) with respect to time. So, consider this two for finding the rotational position of the wheel around the horizontal axle that vary as a function of time.

Now, we denote the both fixed and steerable standard cases separately as $\varphi_f(t)$, $\varphi_s(t)$, and $\varphi(t)$ to show the aggregate matrices. Mathematically it is denoted by;

$$\varphi(t) = \begin{bmatrix} \varphi_f(\mathrm{t}) \\ \varphi_s(\mathrm{t}) \end{bmatrix} \tag{3.22}$$

The time rolling constraint of all wheels given by single expression i.e.

$$J_1(\beta) R(\theta) \dot{Q}_b - J_2 \dot{\varphi} = 0 \tag{3.23}$$

Whereas, $J_1(\beta)$ represent a matrix for all wheels to their motion along their specific wheel plane, and J_2 is a constant diagonal matrix $N * N$ of all standard wheels radii (r).

$$J_1(\beta) = \begin{bmatrix} J_1(\beta_f) & J_{1s}(\beta_s) & J_{1c}(\beta_c) & J_{1sw} & J_{1sph} \end{bmatrix} \tag{3.24}$$

The size of the each matrix is given by $(N_f * 3)$, $(N_s * 3)$, $(N_c * 3)$, $(N_{sw} * 3)$, and $(N_{sph} * 3)$. J_2 is the constant whose diagonal element are the radii of the wheels which are multiplied by $cos\gamma$.

Similarly, sliding constraints of all wheels also given by single equation i.e.

$$\{C_1(\beta)\}\{R(\theta)\dot{Q}_b\} = 0 \tag{3.25}$$

Where, $C_1(\beta)$ defines all over motion in term of sliding of all wheels.

Mathematically it is denoted by:

$$C_1(\beta) = \left[C_{1f} C_{1s}(\beta_s) C_{1c}(\beta_c) C_{1sw} C_{1sph}\right]^T \tag{3.26}$$

3.5 Mobile Robot Maneuverability

This area of mobile robot mainly depend on two things i.e. kinematics mobility of a robot chassis and constraint limiting mobility (also law). Kinematics mobility of a robot chassis is showing probability to navigate in the environment whereas constraint limiting mobility is the law that each wheel must satisfy its sliding constraints. Another is instantaneous kinematics motion by which mobile robot manipulates its position over time by steering steerable wheels. Further, the overall maneuverability of robot is a combination of the existing mobility based on the kinematic sliding constraints of the standard wheels, plus the supplementary freedom attempt by steering and spinning the steerable standard wheels.

3.5.1 Degree of mobility

From the above description or explanations it is clear that the caster wheel, Swedish wheel and spherical wheel not established (enforce, impose) any kinematics constraints on the robot chassis. Due to this only fixed standard wheel and steered standards wheel has been considered for calculating the robot kinematics constraints. Now, consider $(N_f + N_s)$ wheel, to avoid lateral slip.

$$C_{1f} R(\theta)\dot{Q}_b = 0 \tag{3.27}$$

$$C_1(\beta_s) R(\theta)\dot{Q}_b = 0 \tag{3.28}$$

$$C_1(\beta_s) = \begin{bmatrix} C_{1f} & C_{1s}(\beta_s) \end{bmatrix}^T \tag{3.29}$$

Mathematically, the null space of $C_1(\beta_s)$ is the space 'N' such that for any vector 'n' is 'N'.

$$C_1(\beta_s)_* n = 0 \tag{3.30}$$

If the kinematic constraints are to be honored, then the motion of the robot within space 'N'. According to practices, researchers suggested that, a wheeled mobile robot will have zero or more fixed standard wheel as well as steerable standard wheels. Furthermore, this is the point to generate possible range of rank values for any robot i.e.

$$0 \leq [C_{1s}(\beta_s)] \leq 3 \tag{3.31}$$

Now, include the case rank $[C_{1s}(\beta_s)] = 0$, this is only possible if there are zero independent kinematics constraints in $C_{1s}(\beta_s)$. Overall case gives the information about neither fixed nor steerable standard wheel attached to the robot frame.

$$N_f = N_s = 0 \tag{3.32}$$

Similarly, for $[C_{1s}(\beta_s)]$ = 3, the robot is completely constrained in all direction and is, therefore degenerate since motion in the plane is totally impossible.

According to whole phenomenon that is mentioned above we can define a robot's degree of mobility (δ_m):

$$\delta_m = dimN\left[C_{1s}\left(\beta_s\right)\right] = 3 - rank\left[C_{1s}\left(\beta_s\right)\right] \tag{3.33}$$

3.5.2 Degree of steerability

According to number of researches a wheel mobile robot can be steered freely with the number of centred orientable wheel to it. Therefore, degree of steerability can be calculated as:

$$\delta_s = rank\left[C_1\left(\beta_s\right)\right] \tag{3.34}$$

and within the range: $0 \leq \delta_s \leq 2$

3.5.3 Robot maneuverability

It is defined as (i.e. robot maneuverability (δ_M)) the overall degrees of freedom that a robot can handle.

$$\delta_M = \delta_m + \delta_s \tag{3.35}$$

Robot maneuverability for five basic type of three wheel configuration is given in the table.

3.6 Forward Kinematics Model of Mobile Robot

Forward kinematics is the broad description of mechanical behaviour of the robot. In other word, it is the branch of kinematics that describes extensive analysis of robot position and

Table 3.1: Robot maneuverability (δ_M) for five basic types of three wheel configuration.

Wheel Configuration	δ_m	δ_s	δ_M
Omnidirectional (Three Spherical wheels)	3	0	3
Differential(Two Fixed standard wheels and one Spherical wheel)	2	0	2
Omni-steer(Two spherical wheels and one Steered standard wheel)	2	1	3
Tricycle(Two Fixed standard wheel and one Steered standard wheel)	1	1	2
Two Steer(two steered standard wheels and one spherical wheel)	1	2	3

orientation at motion space (robot or local frame) with respect to world space (reference or global frame). Generally, it deals with only input control in Cartesian space with specific variable. It is straightforward and there is no complexity at the time of deriving equations. This section describes the forward kinematics model of the mobile robot and robot changes the direction depending on the velocity profile of each of the wheel. From equation (3.36), we describes the forward kinematics model of robot and calculate the motion of the robot at world frame,

$$\dot{Q}_R = M(\theta)\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} = f\left(l, r, \theta, \dot{\emptyset}_r, \dot{\emptyset}_l\right) \tag{3.36}$$

Where, $\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix}$ presents the robot differential position at global frame i.e. '$\dot{Q}_G$' and '$M(\theta)$' is the rotation matrix.

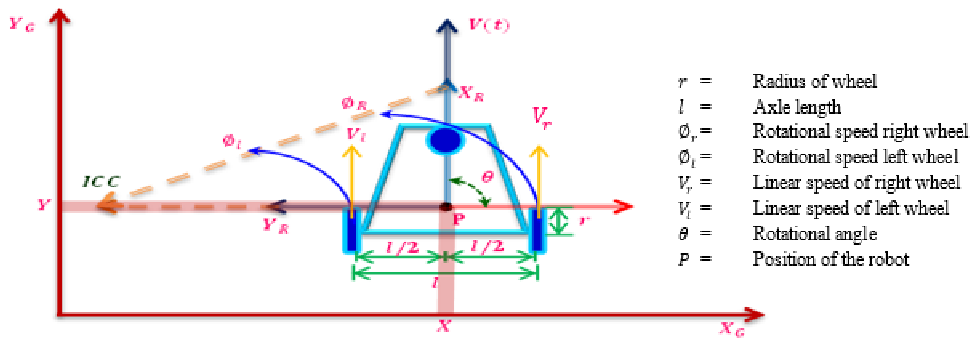


Figure 3.12: Schematic diagram of forward kinematics model for mobile robot.

In general Fig. 3.12 represents the imaginary movement of a mobile robot with two differential wheels and one caster wheel. Where rotation depends on deferential drive of fixed standard wheel at robot space (X_R, Y_R) with respect to global or static space (X_G, Y_G).

From the above Fig, forward kinematics model presents the geometry configuration of simple mobile robot with position and orientation estimation as well as calculates angular velocity (ω) of the wheel with respect to time. Accordingly, it requires accurate measurement of the wheel velocities over time. At the time of navigation each wheel should not perform any slip behaviour and must follow the principle of constraints motion. In addition, all executed constraints must be expressed with respect to the static frame. Due to position and orientation integration over time certain accumulated errors may occur and grow with time.These errors should be estimated for complete and precision control.

To compute the robot's motion in the global reference frame from the local reference frame uses, linear velocity of the right wheel $(V_r) = \frac{r\dot{\varphi}_r}{2}$ and linear velocity of left wheel is $(V_l) = \frac{r\dot{\varphi}_l}{2}$. Since the wheels can't compute sideways motion, Y_R is zero and the angular velocity about θ is calculated from the contribution from the two wheels. Right wheel rotate with angular velocity of right wheel $(\omega_r) = \frac{r\dot{\varphi}_r}{2}$ that is clockwise rotation about point 'P' and the left wheel $(\omega_l) = -\frac{r\dot{\varphi}_l}{2}$ contributes counter-clockwise rotation about P point with a radius of r(Fig. 3.12).

Then, from above equation (3.36) for forward kinematics model:

$$\dot{Q}_G = M(\theta)^{-1}\dot{Q}_R \tag{3.37}$$

put the value of $\dot{Q}_R$ in above equation (3.37), equation becomes

$$\dot{Q}_G = M(\theta)^{-1}\begin{bmatrix} \dot{X}_R \\ \dot{Y}_R \\ \dot{\theta}_R \end{bmatrix} \tag{3.38}$$

Now, put the different velocities i.e. linear and rotational velocities, so X_R is the linear velocity having value $(\dot{V}_r + \dot{V}_l)$ for both wheel as well as velocity of Y_R is zero for both wheel because wheel can't compute sideways velocity and θ_R is the rotational velocity having value $(\omega_r + \omega_l)$, then the equation becomes,

$$\dot{Q}_G = M(\theta)^{-1} \begin{bmatrix} \dot{V}_r + \dot{V}_l \\ 0 \\ \omega_r + \omega_l \end{bmatrix} \tag{3.39}$$

Now, for complete solution of forward kinematics model put the value of variables in equation (3.39), so equation found:

$$\dot{Q}_G = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{\dot{r}\phi_r}{2} + \frac{\dot{r}\phi_l}{2} \\ 0 \\ \frac{\dot{r}\phi_r}{2} - \frac{\dot{r}\phi_l}{2} \end{bmatrix} \tag{3.40}$$

The above equation (3.40) is the solution of the forward kinematics model when robot has two differential wheels and one mobile wheel.

3.7 Holonomicity and Non-holonomicity

In the robotics, for defining the path space of a mobile robot, the model of holonomy is frequently used. In contrast, the term holonomicity refers specifically to the kinematic constraints of the robot frame. A holonomic robot is a robot that has zero non-holonomic kinematic constraints. In other word, holonomic refers to the relationship between the governable and total degrees of freedom of a robot. The robot is said to be holonomic,if the governable degrees of freedom are equal to the total degrees of freedom. For mobile robot, ‘a robot poses holonomicity, if the number of DOF with its movement is equal to the number of global DOF’. Holonomic however, offer full mobility with the same number of degrees of freedom as the environment. This makes path planning easier because there aren’t constraints that need to be integrated. Implementing reactive behaviours is easy because there are no constraints which limit the directions in which the robot can accelerate. Contrariwise, a non-holonomic robot is a robot with one or more non-holonomic kinematic constraints. In another word, if number of governable DOF is less than total number of DOF robot poses non-holonomic model. *An automobile is an example of non-holonomic system.* The vehicle has three DOF-its position in two axes i.e. ‘X’ and ‘Y’ as well as its orientation i.e. ‘θ’ relative to a fixed heading. Yet, it has only two governable DOF i.e. acceleration and the angle of the steering wheel-with which to control its position and orientation. An omnidirectional robot is a holonomic robot if it’s governable DOF = 3.

It should be obvious that motion control for a holonomic system is much easier than a non-holonomic system. A holonomic kinematics constraint can be expressed as an explicit function of position variable only. For example, in the case of mobile robot with a single fixed standard wheel, a holonomic kinematics constraint would be expressed using $\alpha, \beta, \phi, l, r, x, y$ and θ only. Such a constraint requires a differential relationship, such as the derivative of a position variable. Furthermore, it cannot be integrated to provide a constraint in terms of the position variables only. So, non-holonomic systems are often called non-integrablesystems. Following are the properties that can create the difference between holonomic and non-holonomic:

The holonomic mobile robot has the following properties:

⇒ The robot configuration is described by three coordinates. The internal geometry does not appear in the kinematic equations of the mobile robot, so it can be ignored.

⇒ The robot has three DOF without singularities.

⇒ The robot can instantly develop a twist in an arbitrary combination of directions x, y, and θ.

⇒ The robot can instantly accelerate in an arbitrary combination of directions x, y, and θ.

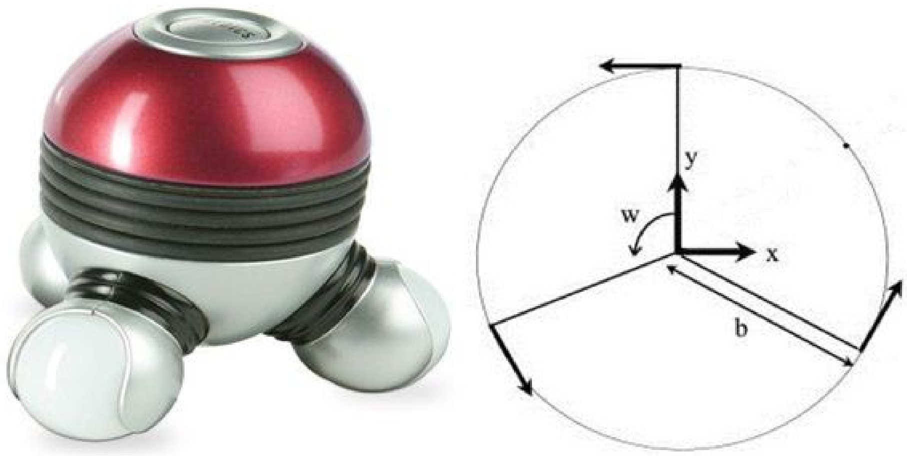


Figure 3.13: Atom-R1 robot represent the holonomicity principle where GDOF=3=TDOF.

The non holonomic mobile robot has the following properties:

⇒ The robot configuration is described by more than three coordinates. Three values are needed to describe the location and orientation of the robot, while others are needed to describe the internal geometry.

⇒ The robot has two DOF, or three DOF with singularities.

Equation (3.41) gives the vehicle state and parametrised by a vector 'X' is non-holonomic, if there exists a constraint 'Q' such that;

$$Q\left(X,\dot{X},\ddot{X},\ldots\ldots\ldots\right)=0 \tag{3.41}$$

Where, the state derivatives can't be integrated out. To illustrate such a constraint, the case of a front wheel steered vehicle have shown in Fig. 3.13. Now, its geometry is written as:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\theta} \end{bmatrix} \times \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} = 0 \tag{3.42}$$

$$Q\left(X,\dot{X},\ldots.\right)=0 \tag{3.43}$$

It means overall $\dot{Q}$ is zero or governable DOF is less than total DOF and case of non-holonomic.

Another condition is redundant. A robot is considered to be redundant,if it has more governable DOF than DOF in its task space. But, a human arm is a holonomic redundant system.It has seven degrees of freedom and there are six physical degrees of freedom in the task of placing the hand. A car's heading (the direction in which it is traveling) must remain aligned with the orientation of the car, or 180 from it if the car is in reverse. It has no other allowable direction, assuming there is no skidding or sliding. Thus, not every path in phase space is achievable; however, every path can be approximated by a holonomic path this is called a *homotopy* principle. The non-holonomicity of a car makes parallel parking and turning in the road difficult. In *homotopy*, it is assumed that the clearance exists.

3.8 Fundamental of Control System

The function of a control mechanism is to maintain certain essential properties of a system at a desired value under perturbation. Historical control systems which are simple but effective have been employed in water regulation and control of liquid level in wine vessels for centuries. However, modern control systems are more complex and own their beginning to the development of control theory.

There have been many developments in automatic control theory during recent year. Unlike conventional control technologies, intelligent controllers are based on Artificial Intelligence (AI) rather than on a plant model. They imitate the human decision-making process and can often be implemented in complex system with more success than conventional control techniques. AI may be classified into expert system, fuzzy logic, artificial neural networks and genetic algorithms. Modern control system may be employing one or more Artificial Intelligence technique in their design.

The earliest significant work in modern automatic control can be traced to James Watt's design [128] of the fly-ball governor for the speed control of a steam engine. Maxwell [129] presented the first mathematical analysis of feedback control. The early twentieth century saw the beginning of what is now known as classical control theory. Minorsky's [130] work on the determination of stability from the differential equation describing the system (characteristic equation) and Nyquist's [131] development of a graphical procedure for determining stability (frequency response) substantially contribution to the study of control theory. Hazen introduce [132] the term "servomechanism" to describe position control system in his attempt to develop a generalised theory of servomechanisms. Based on Nyquist's [133] work H.W Bode introduced a method for feedback amplifier design, now known as the Bode plot.The root locus method of design and stability analysis was developed by W.R Evans [134]. With the introduction of digital computer in the 1960s, the use of frequency response and characteristic equation began to give way to ordinary differential equation (ODE) which worked well with computers. This led to the birth of modern control theory. In many instance, the mathematical model of the plant is simply unknown or ill-defined, leading to generate complexity in the design of the control system. It has been proposed the intelligent control system gives a better performance in such cases.

To discuss control systems, we must first define several key terms.

- ◇ *Input-* Stimulus or excitation applied to a control system from an external source, usually in order to produce a specified response from the system.
- ◇ *Output-* The actual response obtained from the system.
- ◇ *Feedback-* That portion of the output of a system that is returned to modify the input and thus serve as a performance monitor for the system.
- ◇ *Error-* The difference between the input stimulus and the output response. Specifically, it is the difference between the input and the feedback.

3.8.1 Modern Control System

A control system is a collection of physical components assembled together to perform a specific function. System may be electrical, mechanical, hydraulic, pneumatic, thermal, and biomedical or a combination of any of these systems. An ideal control system is one in which an output is a direct function of an input.

The control system may be defined in a variety of way, but the most basic definition is "*A control system is a group of components assembled in such a way as to regulate an energy input to achieve the desired output*". These integrated data through suitable control algorithms send to the actuator and different parts of the robot, to perform collision free navigation inside environments. Here, all equipment's have specific feature by which these are categorise inside mobile robot configuration. A simple robot can have many different tasks to do instantaneously and it is done preciously only by controller. The creation of controller to receive signals from the different sources of the mobile robot (mentioned above) and converted into useful signals, after that transfer into actuator to do useful work towards the target called as controller work. A simple example is the human brain; it gives the signal to the human body to perform different tasks. So, the controller inside mobile robot acts as a brain.

Since arbitrary disturbances and unwanted instabilities can occur at various points in the system, a feedback control system must be able to reject or filter out these fluctuations and perform its task with prescribed accuracies. This function of filtering and smoothing is achieved by using various electrical and mechanical components, gyroscopic devices, accelerometers, etc., and different types of feedback. Feedback control may be defined as the use of different signals, determined by comparing the actual value of system variable to their desired values, as a means of controlling a system. Position feedback is a type of feedback, employed in a system in which the output is either a linear distance or an angular displacement, and a portion of the output is returned or fed back to the input. Position feedback is essential in to control the motion and is used to make the output exactly follow the input. Motion smoothing by means of feedback is accomplished by the use of velocity and acceleration feedback. In the case of velocity feedback, a portion of the output displacement is differentiated and returned so as to restrict the velocity of the output. Acceleration feedback is accomplished by differentiating a portion of the output velocity, which when fed back serves as an additional restriction on the system output. The result of both velocity and acceleration feedback is to aid the system in achieving changes in position without overshoot and oscillation.

The most important features that negative feedback imparts to a control system are; Increment in accuracy, Reduction in sensitivity against disturbance.

For simple mobile robot following are the I/O and O/P parameters for control unit:

◇ Inputs: various sensor readings, camera map, GPS reading, and communication level,

◇ Outputs: speed according to environment, position according to target inside the environment, and orientation according to position and target.

3.8.2 Classifications of Modern Control System

Control systems are classified on the following way:

According to the type of operating technique used in driving:

- *Analogue control system* (“Processing Continuous signal”, process input and control output).
- *Digital control system* (“Processing Discrete signals”, control the output).

According to feedback use (positive, negative):

- *Closed-loop control system with either positive (regenerative) feedback or negative (degenerative) feedback:* The type of system in which output is measured, compared with desired output and maintain at desired level continuously.Here, the system automatically changes the output based on the difference between the feedback signals to the input signal. Example is washing machine; control of water flow. Fig 3.14 shows the simple structure of close loop system.

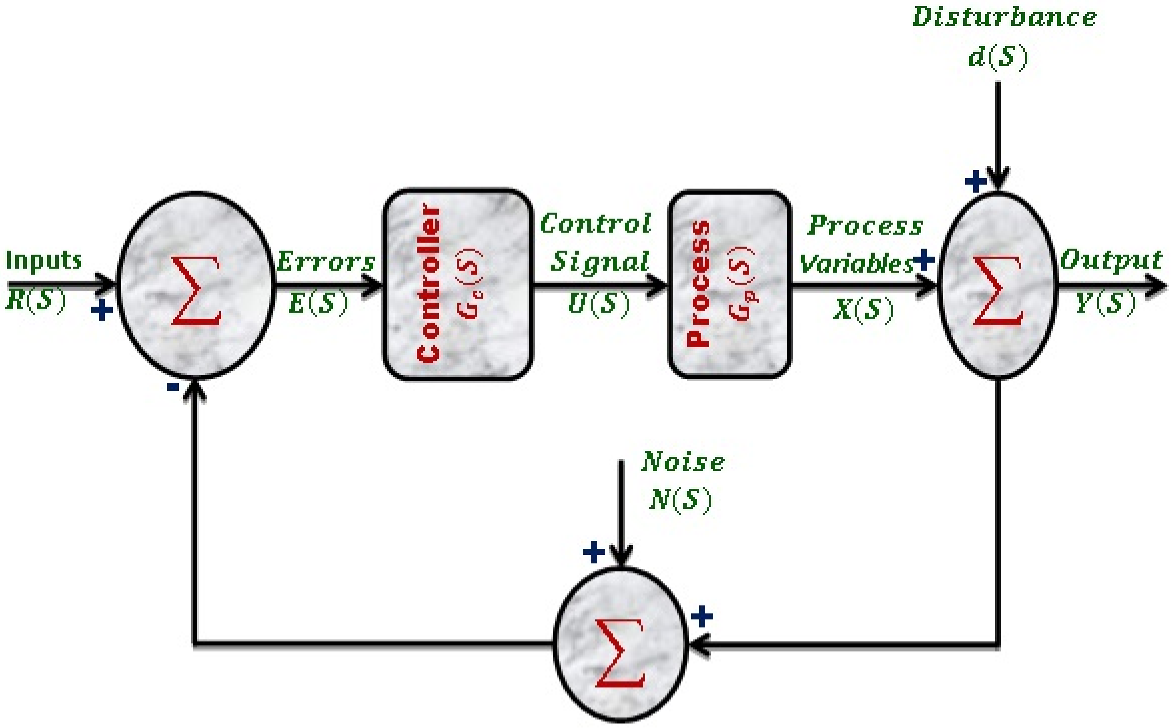


Figure 3.14: Schematic diagram of close loop system.

- *Open-loop control system:* The type of control system that uses only an input signal to actuate an output. There is no feedback to regulate the process, so regulations must be made manually by the operator. Below Fig. 3.15 show the open loop control system.

According to system behaviour:

- *Servomechanisms*
- *Sequential control system*
- *Numerical control system*

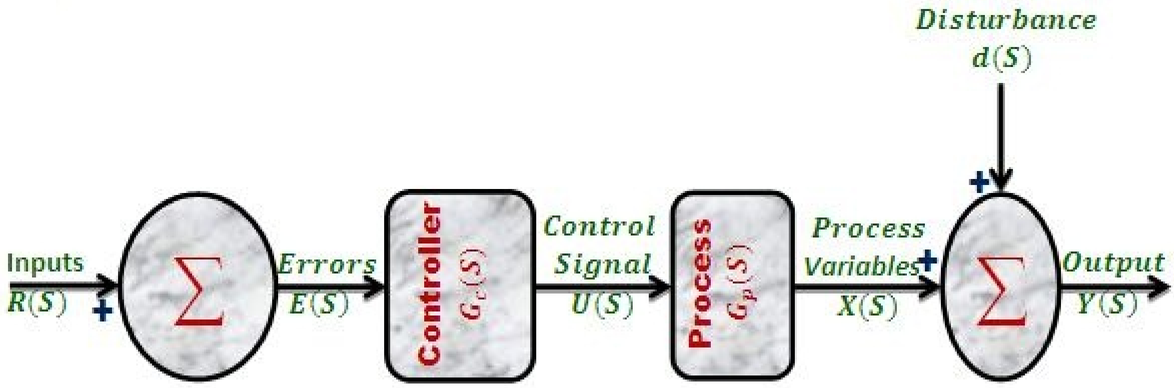


Figure 3.15: Schematic diagram of open loop system.

- *Process control system*

According to generating the control pulses:

- *Single-channel control system*
- *Multi-channel control system*

3.8.3 Characteristics of Control System

Although different systems are designed to perform different functions, all of them have to meet some common requirements. The major characteristics of a typical control system, which is often used as measures of performance to evaluate a system under consideration, are the following:

Stability

The stability of a system relates to its response to inputs or disturbances. "*Systems stability can be defined in terms of its response to external impulse inputs*". A system which remains in a constant state unless affected by an external action and which returns to a constant state when the external action is removed can be considered to be stable. A system is stable if every bounded input produces a bounded output. A system is stable if its impulse response approaches zero as time approaches infinity. The objectives of stability analysis are the determination of the following:

- The degree or extent of system stability

- The steady state performance
- The transient response

Accuracy

The accuracy indicates deviation of the actual output from its desired value and it is a relative measure of system performance. Generally, the accuracy of a control system is improved by using control models such as integral or integral plus proportional.

Speed of response

The speed of response is a measure of how quickly an output attains a steady-state value after the input is applied. A practical system must have a finite response time.

Sensitivity

The sensitivity of a system is a system measure of how sensitive the output is to the changes in the value of physical components as well as environmental conditions. The sensitivity function has an important role to play in judging the performance of the controller because it also describes (from Fig. 3.14) the effect of the disturbance $d(s)$ on the control output $Y(s)$. For the controller to achieve good disturbance rejection, it is obvious that E(s) be made as small as possible by an approximate design for the controller $G_c(s)$.

From the Fig. 3.14,

$$E(s) = R(s) - Y(s) \tag{3.44}$$

$$E(s) = R(s) - [G_p(s).U(s) + d(s)] \tag{3.45}$$

But,

$$U(s) = G_c(s).E(s) \tag{3.46}$$

Putting the values of $U(s)$ in the Eq. 3.45 we get,

$$E(s) = R(s) - G_p(s).G_c(s).E(s) - d(s) \tag{3.47}$$

Now, rearranging these terms,

$$E(s)[1 + G_p(s).G_c(s)] = R(s) - d(s) \tag{3.48}$$

Hence,

$$\frac{E(s)}{R(s)-d(s)} = \frac{1}{[1+G_p(s).G_c(s)]} \tag{3.49}$$

then sensitivity function $\mathscr{E}(S)$ can be written as follow:,

$$\mathscr{E}(S) = \frac{E(s)}{R(s)-d(s)} = \frac{1}{[1+G_p(s).G_c(s)]} \tag{3.50}$$

3.9 Summary

In this chapter kinematic analysis of mobile robot has been carried out. In the next chapter Fuzzy logic controller has been analysed for navigation of mobile robot.

Chapter 4

FUZZY LOGIC AND CONTROL STRUCTURE

In recent years, robots have to play key role in many kinds of industries to construct operational production systems and also to promote automation and unmanned fabrication. *To concern these problems researchers suggested distinctive feature of robot having mobile platform, is that they can change its places according to the jobs and complete the jobs according to task demands by the total fabrication control system.* Accordingly, this chapter presents the enlargement and tentative assessment of a logical method, based on fuzzy logic to localize mobile robots in a brainy space using sensor network.

The modeling of intelligent fuzzy logic based navigator involves an obstacle avoidance behavior and target seeking behavior [7]. The input fuzzy set creates the map demonstrating the mobile robot state in space and resolute by sensor readings to the output fuzzy sets [135] representing the mobile robot in action space. These sensor systems are the collection of autonomous network sensing devices that has integrate sensing, considering the problem capability, loading and erasing the maps, and communication capabilities. The measurements consist of both information about the sensor node location relative to the sensor network, e.g., distance and statistics on the sensor node motion, such as drive estimation gotten from odometers. Fuzzy logic offers controlling tools [80] to illustrate and handle the different aspects of ambiguity in measurements.

The core of this suggested approach, divided into two independent algorithms i.e.:

↪ *The sensor integration network:* It retrieves data from environment by the help of sensor network and produces a compact depth image, i.e. disparity map, of the scene.

↪ *The fuzzy decision making algorithm:* It examine the data for previous section and adopt the finest direction for navigation of robot and avoid obstacles, based on a simple fuzzy inference system (FIS).

This chapter describes the navigation control technique of mobile robot in anonymous environs with obstacles avoidance and prepares sensor-based control architecture for mobile robot navigation in anonymous environs using fuzzy based technology.

4.1 Introduction

In recent years, the use of fuzzy logic or fuzzy set theory being extensively used to develop suitable mobile robot control algorithm due to its easier technical skills over mathematical form as well as for development of control architecture for complex system like, the unit of washing machine to speedboats, a simple mobile robot to space mobile robot and air condition units to hand-held autofocus cameras. Here, fuzzy logic is exemplified with respect to navigation system of a mobile robot.

The control engineers have usually trusted on mathematical models for their design. However, if system is more complex; the mathematical model is less effective. This kind of philosophy create the researcher attention towards the motivation of fuzzy logic, which formulized by Zadeh the founder of fuzzy set theory [84], as the principle of incompatibility. Zadeh stated that "*As the complexity of the system increase, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) became almost mutually exclusive characteristics*" [136].

4.2 Historical Review

The term 'fuzzy' in fuzzy logic was first coined in 1965 by Professor Lofti Zadeh, then chair of UC Berkeley's Electrical Engineering Department. He used the term to describe multi-valued sets in the seminal paper, 'Fuzzy Sets' [135]. The work in his research is derived from multivalued logic, a concept which emerged in the 1920 to deal with Heisenberg's Uncertainty Principle in quantum mechanics. Multivalued logic was further developed by distinguished logician such as Jan Lukasiewicz, Bertrand Russell and Max Black [126,137]. At that time, multivalence was usually described by term 'vagueness'. When Zadeh developed his theory, he introduced the term ‘fuzzy’.

Zadeh applied Lukasiewicz’s multivalued logic to set theory and created what he called fuzzy sets: sets whose elements belong to it in different degrees. According to the fuzzy principle, ‘everything is a matter of degree’. While conventional logic is bivalence i.e. based on either *TRUE* or *FALSE* as well as fuzzy logic is multivalence that value vary from ‘0’ to ‘1’ . But with modern science, it shift from conventional mathematics and number crunching to philosophy and language. At the beginning, fuzzy logic remained very much a theoretical concept with little practical application. The work Zadeh was involved in consisted mainly of the computer simulation of mathematical ideas. In the 1970, Professor Edrahim Mamdani [138] of Queen Mary College, London, built the first fuzzy system, a steam engine controller, and later the first fuzzy traffic lights. This led to the extensive development of fuzzy control applications and products seen today.

4.3 Linguistic variables

The concept of a linguistic variable, a term which is used to describe the input and outputs of the FLC, is the foundation of fuzzy logic control system. A conventional variable is numerical and precise. It is not capable of supporting the vagueness in fuzzy set theory. By definition, a linguistic variable is made up of words, sentences or artificial language, which are less precise then number. It provides the means of approximate characterisation of complex or ill-defined phenomena. For example, ‘AGE’ is a linguistic variable whose value may be the fuzzy sets ‘YOUNG’ and ‘OLD’. A more common example in fuzzy control would be the linguistic variable ‘ERROR’, which may have linguistic values such as ‘positive’, ‘zero’ and ‘negative’. In this thesis the following convention are used to define linguistic variables. If ‘X_i’ is a linguistic variable defined over the universe of discourse ‘U’ where ‘x ∈ U’

then,

LX_i^k (for k=1,.........n) are the lingustic values X_i can take.

‘n’ is the number of lingustic values X_i have.

$\mu_{LX_i^k}$,k(x) is the LX_i^k membership function for the value 'x'

LX_i is the set containing LX_i^k,where $[LX_i = LX_i^1, LX_i^2, ...LX_i^n]$

In the example above:

X_1 is 'ERROR'

$n = 3$ is the number of lingustic values in X_1

LX_1^1 is 'POSITIVE'

L_1^2 is 'ZERO'

LX_1^3 is 'NEGATIVE'

and, for $\{x = -1, 0, 1 :\}$

$$\mu_{LX_1^1}(-1) = 0; \qquad \mu_{LX_1^1}(0) = 0; \qquad \mu_{LX_1^1}(1) = 1; \tag{4.1}$$

$$\mu_{LX_1^2}(-1) = 0; \qquad \mu_{LX_1^2}(0) = 1; \qquad \mu_{LX_1^2}(1) = 0; \tag{4.2}$$

$$\mu_{LX_1^3}(-1) = 1; \qquad \mu_{LX_1^3}(0) = 0; \qquad \mu_{LX_1^3}(1) = 0; \tag{4.3}$$

4.4 Categorization of membership functions

Fig.4.1 indicates the different categories of membership functions, which are normally used in fuzzy logic theory and nature of shape depends upon on the related application. For control application by fuzzy logic, generally 'Gaussian, bell-shaped and S-shape function' are not frequently used. To the contrary, L-function, Γ-function and Λ-function are far more common.
As a result, following definitions has been made in mathematical form [84]:

For Γ-function, Γ:U→[0,1]

$$\Gamma(x;\alpha,\beta) = \begin{cases} 0 & x < \alpha \\ (x-\alpha)/(\beta-\alpha) & \alpha \le x \le \beta \\ 1 & x > \beta \end{cases} \tag{4.4}$$

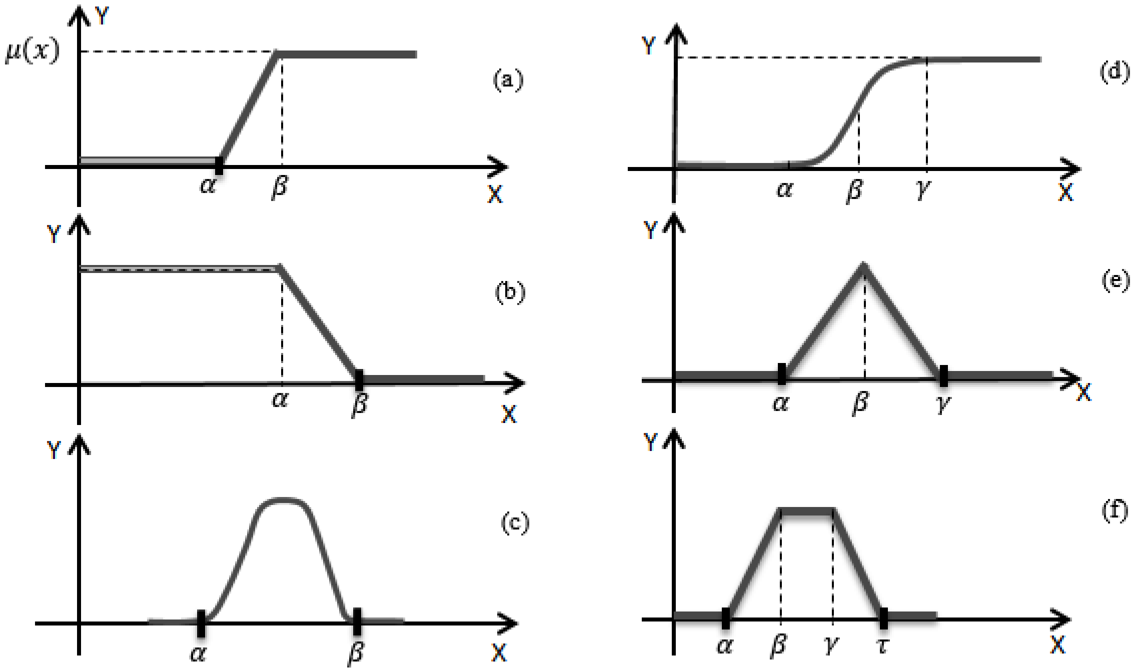


Figure 4.1: Different types of membership function

For L-function, L:U→[0,1]

$$L(x;\alpha,\beta)=\begin{cases}0 & x<\alpha\\ (x-\beta)/(\alpha-\beta) & \alpha\le x\le\beta\\ 1 & x>\beta\end{cases}\tag{4.5}$$

For Λ-function, Λ:U→[0,1]

$$\Lambda(x;\alpha,\beta,\gamma)=\begin{cases}0 & x<\alpha\\ (x-\alpha)/(\beta-\alpha) & \alpha\le x\le\beta\\ (x-\gamma)/(\beta-\gamma) & \beta\le x\le\gamma\\ 0 & x>\gamma\end{cases}\tag{4.6}$$

4.5 Fuzzy Control Structure

Fig.4.2 shows the simple block diagram of a fuzzy logic controller (FLC). Ross [139] in his book 'Fuzzy logic with Engineering Application' describes the theory of system based on classical set theory and Fuzzy set theory and are given below:

◇ Fuzzyfication module

- ♢ Knowledge base
- ♢ Rule base
- ♢ Inference engine
- ♢ Defuzzification module

Automatic change in the design parameter of any of the five elements creates an adaptive fuzzy controller. Fuzzy control systems with fixed parameters are non-adaptive. Other non-fuzzy elements which are also part of the control system include the sensors, the analogue to digital converters, the digital to analogue converters and the normalization circuits. There are usually two types of normalization circuits: one maps the physical values of the control inputs onto a normalised universe of discourse and the other maps the normalised value of the control output variables back onto its physical domain.

4.6 Hybridization of Membership functions for Control Structure

In this research, we hybridize the fuzzy membership functions to attain the precious fuzzy controller. Accordingly, three types of membership function have been hybridized in a single control structure such as Triangular, Trapezoidal and Gaussian. To conduct the theoretical analysis with five linguistic variables, for functional parameters (i.e. obstacle distance, heading angle and velocity), these membership function taken as "first and fifth *MF* taken as Triangular, second and fourth MF taken as Trapezoidal and the third *MF* is Gaussian".

To categorize the Left, Right and Front Obstacle distances during navigation of mobile robot, the linguistic variables recognize with terms such as "very near", "near", "medium", "far" and "very far". When the target is located at the left side of the mobile robot, the target angle is negative and if the target is at right side of robot, the angle defined as the term "no target consider" is used if there is no target in the environment. "More positive", "positive", "zero", "negative" and "more negative" are defined for the bearing of heading angle (HA) with respect to target.

Linguistic variables such as "very slow", "slow", "fast", "very fast" and "vv fast" are considered for left wheel and right wheel velocity. The membership functions for the inputs

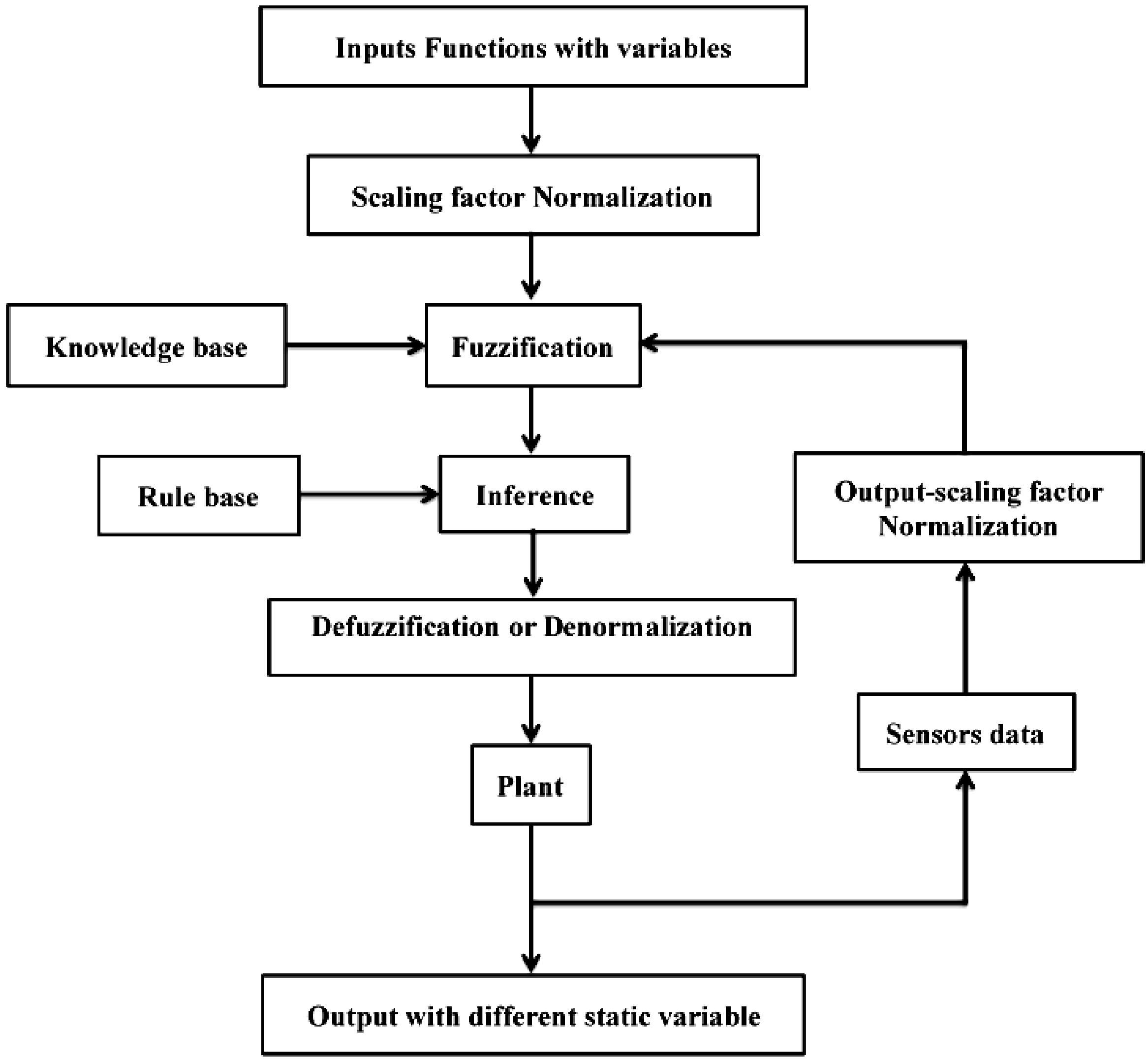


Figure 4.2: Block diagram represent the process of a typical fuzzy logic controller

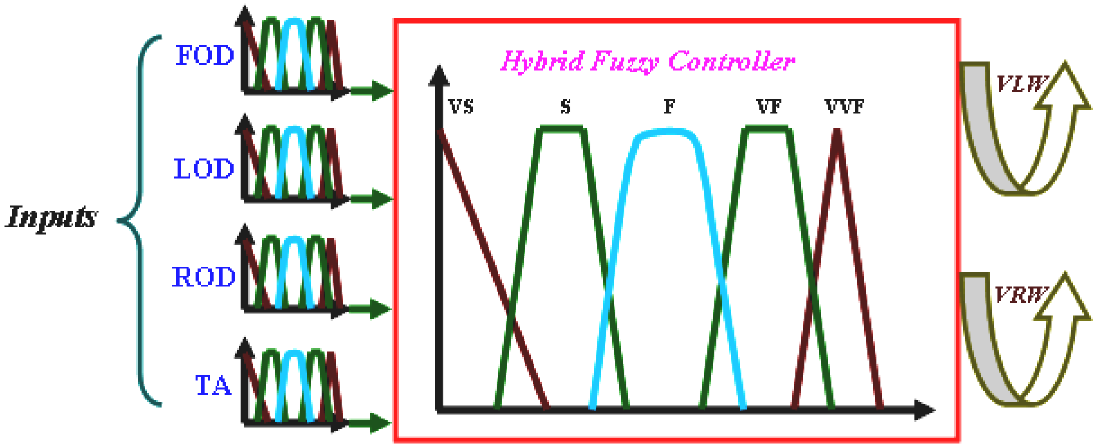


Figure 4.3: Hybrid Fuzzy Controller embedded with Integration of Different Membership Functions for Mobile Robot Navigation

and outputs along with the range of these functions are shown in the 'Table 4.1,4.2,4.3'. Values of parameters are decided empirically. The membership functions described above are shown in Fig 4.3.

Table 4.1: Different parameters for Obstacle Distance

Variables (MF)	Parameters for Left, Right and Front Obstacle Distance (in Mt.)			
Very Near	0.0	to	0.14	(0.0-0.07-0.14)
Near	0.07	to	0.21	(0.07-0.14-0.21)
Medium	0.14	to	0.28	(0.14-0.21-0.28)
Far	0.21	to	0.35	(0.21-0.28-0.35)
Very Far	0.28	to	0.42	(0.28-0.35-0.42)

Table 4.2: Different parameters for Heading Angle

Variables (MF)	Parameters for Heading Angle(in degree)			
More Negative	-90	to	-30	(-90, -60, -30)
Negative	-60	to	0	(-60, -30, 0)
Zero	-30	to	30	(-30, 0, 30)
Positive	0	to	60	(0, 30, 60)
More Positive	30	to	90	(30, 60, 90)

4.7 Rule Base for Proposed FLC

The distance between the robots and obstacles act as repulsive forces for avoiding the obstacles. When the robot is very close to an obstacle, the robot must change its speed and

Table 4.3: Parameters for Left and Right Velocity

Variables (MF)	Wheels Velocity in m/s			
Very Slow	0.0	to	1.6	(0.0, 0.8, 1.6)
Slow	0.8	to	2.4	(0.8, 1.6, 2.4)
Fast	1.6	to	3.2	(1.6, 2.4, 3.2)
Very Fast	2.4	to	4.0	(2.4, 3.2, 4.0)
Very Very Fast	3.2	to	4.6	(3.2, 4.0, 4.6)

heading angle to avoid the obstacle. When the readings from any sensor are less than the minimum threshold values, the robot determines an object is close, and then obstacle avoidance behavior is activated. Collision avoidance has the highest priority, so, it can override the other behaviors.

Some rules mentioned in 'Table 4.4,4.5,4.6' for five-membership function, cater for extreme conditions when an obstacles have to be avoided as quickly as possible. In 'Table. 4.4' rule 16 (for OAA = obstacle avoidance algorithm) contains the left obstacle distance as "Medium", right obstacle distance as "Near", front obstacle distance as "Very Far" and no target is located around the robot, then the robot should move front side to avoid collision with the obstacle. For the above condition the velocity of both wheels should equal and "V fast". The Simulation result of static obstacle avoidance has been exhibited in Fig 4.5.

In the absence of wall following behavior in corporation with obstacle avoidance behavior the robot is inexpert of reaching the goal position when it en-counts dead end obstacles on their path. When the robot is moving to a specified target through a narrow channel, the robot should keep on heading towards the goal position, but the robot also comes closer to the obstacles. Initially, robot runs directly towards target as obstacles are sensed far away from it. But if it senses obstacles at the front it will make a left or right turn to avoid it.

If target is at right side of it, the behavior of the approaching target tries to make it turn to the right and target orientation increases gradually. Even at the right side also, robot is facing obstacle in the form of wall, then it will try to avoid it by making a left turn. Due to the nature of achieving target using shortest path, robot will again turn to the right to make itself target oriented. Thus it will be trapped in an indefinite loop. To avoid this loop, the robot must have the wall following behavior

In 'Table. 4.5' some fuzzy rules show that the robot shall follow wall or an edge of an obstacle when the obstacle is very close to the right or left of the robot, and the target also is located to the right or left. Wall following behavior also depends on target orientation from the current position of the robot. But these rules are not considering the target angle. Rule 5 (for OAA and WFB = wall following behavior) contains the left obstacle distance as “Medium”, right obstacle distance as “Medium”, front obstacle distance as “Very far” and no target is located around the robot, then the robot should move quickly towards front to avoid collision with the obstacle in left and right of it. For the above condition the right wheel velocity left wheel velocity should be fast to maintain the straight forward direction. The simulation result of wall following has been shown in Fig 4.5 (b) and escaping from dead.

The attractive force between the robot and the target causes the robot seeking towards the target when the robot is very close to the target. It is used to change the direction of the robot toward the target when there are no obstacles blocking the robot.

Considering rule no 5 (For TA = Target Seeking) in ‘Table. 4.6’, if the left obstacle is at “Near”, the right obstacle is at “Very Far”, the front obstacle is at “Far” and the robot detects a target located on its right side (or positive side), then the robot should turn right as soon as possible. For approaching target, the right velocity of the robot should be slow and the left velocity should be *very fast*.

4.8 Layout for Navigation

Every autonomous mobile robot desires some detecting devices first to get perception of environ and then travel in this environ. Environmental perception is the core for research of mobile robot, and has countless application value. Because, navigation of mobile robot based on surrounding information and according to this information, it navigates inside environment, avoid barriers and execute the given task. When an autonomous mobile robot moves in unknown or slightly known environment, at that time it uses several sensing devices to know the environmental uncertainty as well as for path planning. Various types of sensors characteristically used according to purpose of sensing environment. For example; laser range finders, sonar sensor, infrared sensors, ultrasonic sensors and vision systems.

This experiment used infrared sensors to obtained data from environments, such as distance measurement and a vision system for object-boundary detection. The suggested algorithm also delivers constraints to the system by fuzzy-sensor network that filter out

Table 4.4: List of Rules for Obstacle Avoidance

Rule No.	Action	LOD	FOD	ROD	HA	VLW	VRW
1	OAA	V Near	V Near	V Near	NTC	V Slow	V Slow
2	OAA	Near	V Near	V Near	NTC	V Slow	Slow
3	OAA	Medium	V Near	V Near	NTC	Fast	Slow
4	OAA	Far	V Near	V Near	NTC	V Fast	Med
5	OAA	V Far	V Near	V Near	NTC	Med	V Fast
6	OAA	Near	Near	V Near	NTC	Slow	Slow
7	OAA	Medium	Near	Near	NTC	Fast	Slow
8	OAA	Far	Medium	Near	NTC	Fast	Med
9	OAA	V Far	Near	Near	NTC	V Fast	V Slow
10	OAA	Far	V Far	Near	NTC	Fast	V Fast
11	OAA	V Far	Medium	V Near	NTC	V Fast	V Slow
12	OAA	Far	Near	V Near	NTC	V Slow	Fast
13	OAA	V Far	Near	Near	NTC	V Slow	V Fast
14	OAA	Medium	Near	Near	NTC	Slow	V Slow
15	OAA	Far	Near	Near	NTC	Med	Slow
16	OAA	Medium	V Far	Near	NTC	V fast	Slow
17	OAA	Medium	Far	Near	NTC	Med	Slow
18	OAA	Far	Medium	Near	NTC	Fast	Med
19	OAA	Near	Medium	Near	NTC	Slow	Slow
20	OAA	Near	Medium	Far	NTC	Med	Slow
21	OAA	Far	Medium	Near	NTC	Med	Slow
22	OAA	Medium	Medium	Near	NTC	Slow	Slow
23	OAA	Medium	Medium	V Far	NTC	V Fast	Med
24	OAA	V Near	V Near	Far	NTC	V Fast	Slow
25	OAA	Near	Far	Near	NTC	Slow	Med
26	OAA	Near	Far	Medium	NTC	Med	Fast
27	OAA	Far	Far	Near	NTC	Slow	Fast
28	OAA	Far	Far	Medium	NTC	Slow	Med

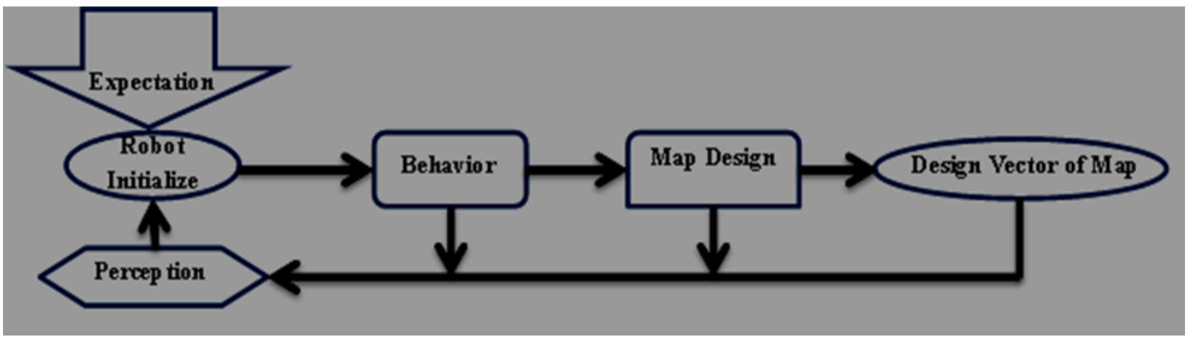


Figure 4.4: Perception flow chart of mobile robot

Table 4.5: List Of Rules For Obstacle Avoidance And Wall Following

Rule No.	Action	LOD	FOD	ROD	HA	VLW	VRW
1	OAA,WFB	V Near	Near	V Near	NTC	V Slow	V Slow
2	OAA,WFB	V Near	Medium	V Near	NTC	Med	Med
3	OAA,WFB	Near	Medium	V Near	NTC	Slow	Fast
4	OAA,WFB	V Near	Far	V Near	NTC	Fast	Fast
5	OAA,WFB	Medium	V Far	Medium	NTC	V Fast	V Fast
6	OAA,WFB	Medium	Far	Medium	NTC	Fast	Fast
7	OAA,WFB	Near	Far	Medium	NTC	Fast	Med
8	OAA,WFB	Near	Far	Medium	NTC	V Fast	Fast
9	OAA,WFB	Near	V Far	Near	NTC	V Fast	V Fast
10	OAA,WFB	Medium	Far	Near	NTC	Med	Fast

Table 4.6: List Of Rules For Target Seeking

Rule No.	Action	LOD	FOD	ROD	HA	VLW	VRW
1	TA	V Near	Near	Far	Pos	V Fast	Slow
2	TA	V Near	Far	Near	Zero	Fast	Fast
3	TA	V Near	Med	V Far	More Pos	V Fast	V Slow
4	TA	Near	V Far	V Far	Negative	V Slow	Med
5	TA	Near	Far	V Far	Pos	V Fast	Slow
6	TA	Near	Med	V Far	Zero	Med	Slow
7	TA	Med	Far	Near	Negative	Slow	Med
8	TA	Med	V Near	Far	More Pos	Fast	V slow
9	TA	Med	Near	Far	Negative	V Slow	Med
10	TA	V Far	V Far	Med	More Neg	V Slow	V Fast
11	TA	V Far	V Far	V Far	Zero	V Fast	V Fast
12	TA	Far	Near	V Near	More Neg	Slow	V Fast
13	TA	Far	Med	Near	Zero	Med	Fast
14	TA	Far	V Far	Near	Neg	Med	V Fast

incorrect data from the sensor readings. The sensors used here deliver a comparatively precise measurement of the distance to an object with angular resolution.

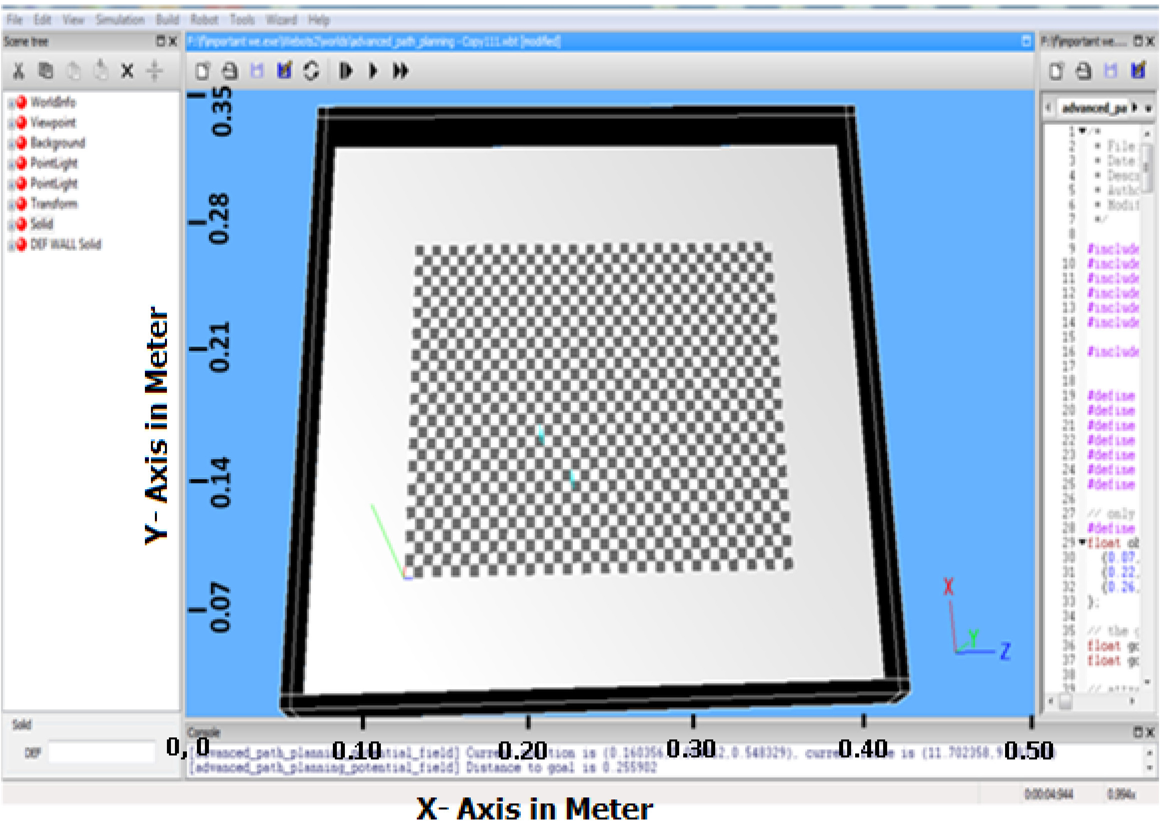
Fig. 4.4 show the flow diagram of mobile robot navigation i.e. how to initialize the perceptional view based on perception of environment. For perception of environment, it uses infrared sensors. At each navigation stage, it always update vector of map with new environmental data by sensor fusion with sensor integration.

4.9 Results and Discussion

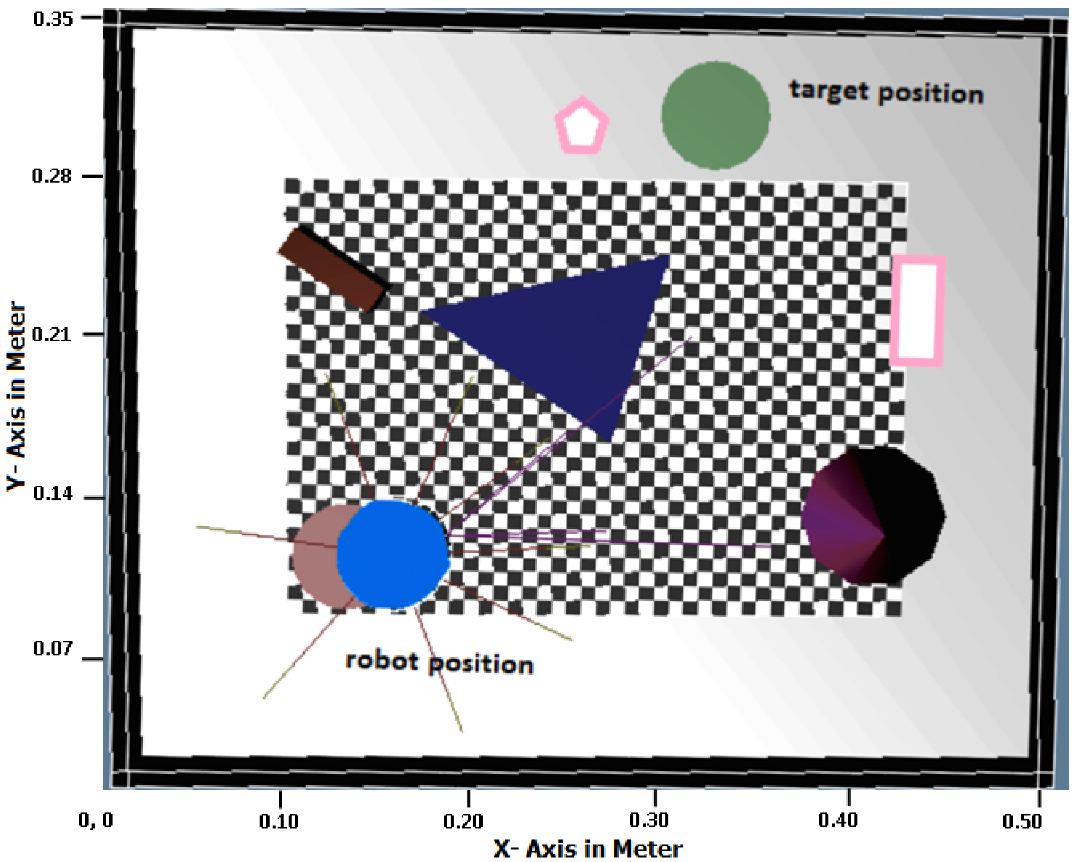
4.9.1 Navigation in Simulated Environment

The combination using "Fuzzy Logic and sensor network" instead of probabilistic rules approach few advantages. Primarily, it has less concentration for computational structure and secondly, by setting the fuzzy sensor network in a proper manner; reduces the map errors obtained by the sensors observation, and obtain extreme accuracy at every stage of path that follow by mobile robot. However, proposed algorithm uses infrared sensors that estimate location and position of the robot but the concept can easily be extended with many sensors. The result obtained in this proposed work depends upon both, sensors reading and fuzzy technique. The interesting case occurs if the one of the sensors gives inaccurate results or if the sensor readings are correct but the robot's own original confidence in its location is misplaced. For this case, the fuzzy rules help to filtered out the data and attained by setting up fuzzy rules, so that if two of the three assertion trials match, the third could be given less importance. Fig 4.5 showed the trajectory details of mobile robot as well as the proposed mobile robot model. It has infrared sensor for detection and vision purpose.

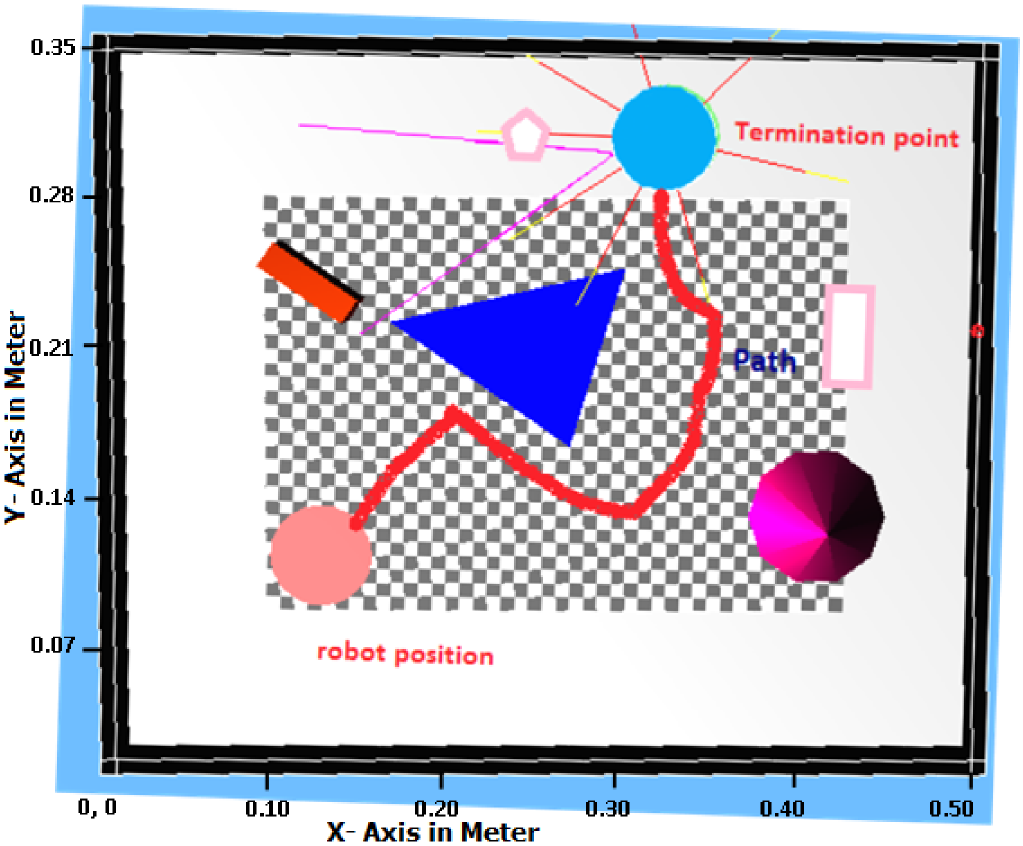
Fig 4.5 (c) contain three sections, first part is screen tree that show that physical structure of mobile robot, second part show that simulation environment at which robot simulated before implemented in realistic world that contain boxes as obstacle (Fig. a), green ball as a target, red ball as an initial position and blue circle (contain sensors ray) as a mobile robot. The proposed work based on combination of fuzzy logic with sensor network and provides collision free navigation to the robot on mobile platform, at which if any data provided by sensor creates errors at that time fuzzy rule helps to obtain precious data for motion. Simulation result show that mobile robot avoid the obstacle in efficient manner and achieve the target without collision with wall and obstacle.


0.35
0.28
0.21
0.14
0.07
Y - Axis in Meter
0, 0
0.10
0.20
0.30
0.40
0.50
X- Axis in Meter

(a)


target position
robot position
0.35
0.28
0.21
0.14
0.07
Y - Axis in Meter
0, 0
0.10
0.20
0.30
0.40
0.50
X- Axis in Meter

(b)



(c)

Figure 4.5: (a) presents the three section of simulation environment (b) the complete trajectory of simulated environment (c) represent the trajectory with path from initial point to termination point

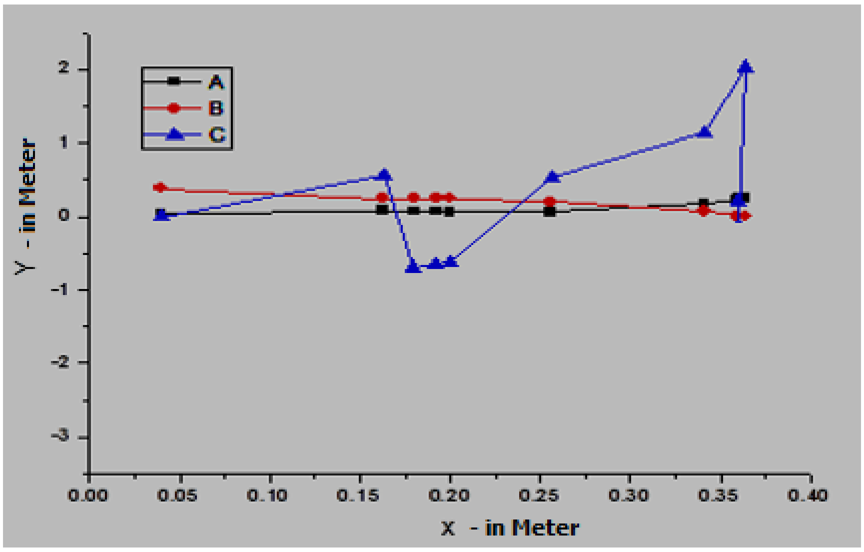


Figure 4.6: Indicate the graph according to simulation data.

Table 4.7: Robot navigation simulation data with three obstacle and target

Stages	X-Direction	Y-Direction	θ	Dist. between robot and target
1	0.040	0.040	0.000	0.380
79	0.163	0.086	0.553	0.252
158	0.180	0.077	-0.693	0.245
237	0.192	0.067	-0.648	0.244
316	0.200	0.061	-0.619	0.243
395	0.256	0.064	0.538	0.206
478	0.341	0.169	1.137	0.077
553	0.364	0.246	2.030	0.0047
632	0.3595	0.241	-0.133	0.00316
711	0.3599	0.247	-3.073	0.00245
789	0.360	0.243	0.214	0.002004

Table. 4.1,4.2,4.3 indicate the navigational simulated data, when sensor integration through sensory network is conducted for robot over time. The experiment covers 789 simulation stages within 1 minute at the time of motion, from static point to termination point.

In graph ‘A’ represent the graph between ‘X’ direction and distance of target from robot position. Similarly, ‘B’ represents the graph between ‘Y’ direction and distance of target from robot position. Finally, ‘C’ represents the path with all values such as ‘X’, ‘Y’, and ‘θ’ etc.

So, eleven number of data is provided due to large data scale with simulation and each

Table 4.8: Indicates the obstacle position in 'X' and 'Y' direction

No. of Obstacle	In X-Direction	In Y-Direction
1	0.07	0.21
2	0.22	0.09
3	0.26	0.05
4	0.29	0.22
5	0.33	0.20

data stage indicated by Table 4.7 contain simulation gap of 78 stages from 1st to 2nd and 2nd to 3rd stage and so on. In addition, Table 4.7 contain motion of robot in X, Y and θ direction as well as updated distance between robot and target at each simulation stage. This is covered by combine effect of fuzzy logic and sensory network algorithm, that provides fast and smother navigation to the robot. Table 4.8 presents the obstacle position inside environment and given by Fig. 4.5.

To develop control algorithm webots simulation platform is used. To express the control structure, webots uses two different time steps, i.e. control time step (specified in the control algorithms) and simulation time step (specified in the scene tree).

4.9.2 Experimental Environment Setup and control structure

For the experimental study on realistic world; model of Hemisson robot is used. The surface area taken for realistic world experiment consuming, width of the area = 0.5 meter and height of the area= 0.35 meter. The robot environment holds five obstacles, shifted at the scale specified in 'Table 4.8' as well as target with location 0.36 at 'X' or 0.245 at 'Y' approx., presented by Fig. 4.7. For experimental simulation, position of the robot inside environment given by 0.040 at X-axis and 0.040 at Y-axis subjected to static mode.

To reach the target position (experimental study) from its initial position, time taken by the robot is 1:18:524 minute and the length of the path indicated by simulation graph in Fig. 4.7 by red line. It has been noticed that, the path covered and time taken (1:04:992) by robot during simulation is less, compaired to experimental study.

In addition both of two (i.e. simulation time step) are independent to each other and that is the main reason for fast simulation. If simulation time step is 16 milliseconds, at that time the control time step is 32 and 64 milliseconds taken. For example, if the update delay

Table 4.9: Overall path length, time taken and errors between results

Algorithm	TSR (P)*	ESR (P)*	TSR (T)*	ESR (T)*	ERROR
FLC	*0.796*	*0.804*	*00:50:960*	*00:52:524*	*1.0050*

***Note: In Table 4.9**

"TSR (P)" = Theoretical Simulation Result Related to Path Length (in meter).

"ESR (P)" = Experimental Simulation Result Related to Path Length (in meter).

"TSR (T)" = Theoretical Simulation Result Related to Time Taken (in minute).

"ESR (T)" = Experimental Simulation Result Related to Time Taken (in minute).

"ERRORS" = Between Path Length i.e. TSR and ESR

is chosen to be twice the control time step at that time sensor data will be updating after every two robot step.

4.10 Summary

The control architecture for robot in real time environment is a sensor-network fuzzy based algorithm in indoor environs as presented in this chapter. We expect that use of the prediction of the sensory readings may improve the control quality. Good results achieved exemplify the robustness of a fuzzy logic with sensor networks. The use of perceptional equilibrium allows perceptionaction scheduling with compact sensor space magnitudes. Simulation and Experimental investigation offers to show the efficiency of the proposed plan in usually real time obstacle condition. The localization scheme and fuzzy-base sensor navigation are described in brief. The experimental results clearly indicate the mapping of multiple inputs to outputs with optimum path in every control cycle of the robot navigation. The path length with respect to time is given by Table. 4.9. This approach involves the natural way of dealing with the environments using simple linguistic logic rules without using intensive mathematical model. The knowledge base of each behavior rule is easy to figure out, because it captures the behavior rules in a linguistic form. The strength of the proposed methodology is the mapping of the inputs to the output through compositional association of multiple input variables. Utilization of the proposed methodology for other applications requires minimum modifications during setting of input and output linguistic variables. Fi-

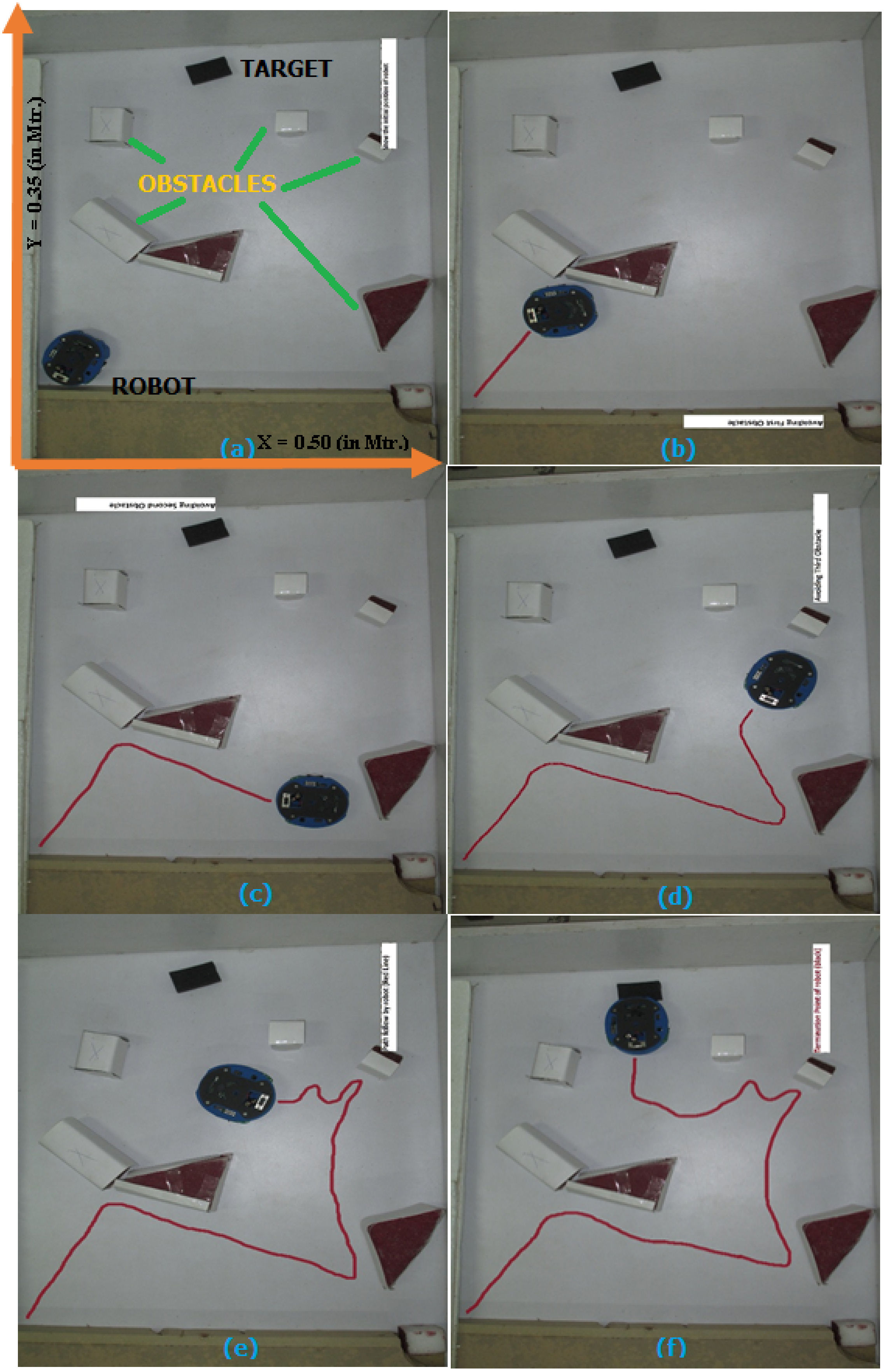


Figure 4.7: Complete trajectory of realistic environment

nally, the effectiveness and the efficiency of the proposed algorithm are demonstrated by simulation as well as experimental studies. Obstacle avoidance behavior is shown in both simulation (Fig. 4.5) and experimental (Fig. 4.7) results using fuzzy logic.

Chapter 5

NAVIGATION USING TYPE-2 FUZZY LOGIC CONTROLLER

Fuzzy systems enable a machine to take decisions as the human mind. To improving the decision making process becomes a necessity and this evolutions required for machines that has mobile platform. In order to do the same, we have to decrease the opacities present in the decision making process. Hence, we implement another methodology (type 2 fuzzy logic) with the system, that would reduce variances and advance the decision making process. This chapter gives us an overview of such process using type-2 fuzzy logic.

5.1 Introduction

The mobile robot navigation for real time environment is one of the most important requirements for the present day of robotics research. Accordingly, most of the research related to this field poses some of the common drawbacks such as, expensive equipment, large computation data, hard implementation and the difficulty with system design. The work presented in this chapter deals with type-2 fuzzy controller and use sensor network to recognise the environmental uncertainty and create collision free path.

The value of robotic model, based on perceptive approach for the design of intelligent mobile robots is restricted due to unknown and unstructured environments, variable and imperfect perceptual information and indefinite actuators. For several working platform (space research, underwater robot, autonomous vehicle etc.) the robot's environment changes time to time and that is not predictable by the researchers in advance. In addition, the information about the environment taken by the vision system of robot is often rough and inadequate due to the limited version of perceptual quality of sensors. Consequently, for qualitative and complete development of navigation controller, it is important to take dynamic judgements and selections at right time. Consequently, to increase efficiency and effectiveness of the process, it is necessary to have a consultative system (i.e. AI control algorithm) that can offer compensations of knowledge based methodology.

The fuzzy rules describe the relation between the exterior and interior conditions of the robot inside environment and set the possible actions. The most common way is to construct the FLC by stimulating the fuzzy rules and the membership functions based on professional knowledge or through the observation of the actions of a human operator that controlling the mobile robot.

In type-2 fuzzy systems, we have reduce type-1 fuzzy sets within systems, so that more uncertainty can be avoided. From the beginning of fuzzy logic set theory, excoriation has been made about the fact, that the membership function of a type-1 fuzzy set has no uncertainty linked with it. This challenges the word fuzzy, as it has the potentials of lots of uncertainties. Zadeh [84], proposed a more classy kind of fuzzy set, the first of which was called a type-2 fuzzy set. Type-2 fuzzy set permit us to accommodate uncertainty about the membership function into fuzzy set theory, and creates a way to address the criticism of type-1 fuzzy sets head-on. But, if there is no uncertainty, then a type-2 fuzzy set reduces to a type-1 fuzzy set that is analogous to probability reducing to determinism when unpredictability vanishes.

Type-1 (F1) Fuzzy logic systems has restricted capacity to handle data uncertainties [140]. When a type-1 membership function has been defined, uncertainty vanishes because a type 1 membership function is precise [87]. On the other hand, type-2 fuzzy logic systems make this convenient to handle uncertainties in a better way than F1. Due to presence of different rules; rules contain linguistic variables, and implemented inside fuzzy 2 system that includes a footprint of uncertainty (FOU) [141], it captures more uncertainties rather than F1 fuzzy set systems. In addition, type 2 fuzzy sets do not cover crisp membership functions, on the opposite F1 sets cover crisp membership grades [142].

The simple FLCs has common problem, i.e. they can't completely handle or accommodate the linguistic and geometric uncertainties linked with fluctuating and dynamic environment because they use precise fuzzy sets. In recent times, Mendel and Karnik [85] have established a type-2 fuzzy logic system, this technique can switches vague and uncertainty

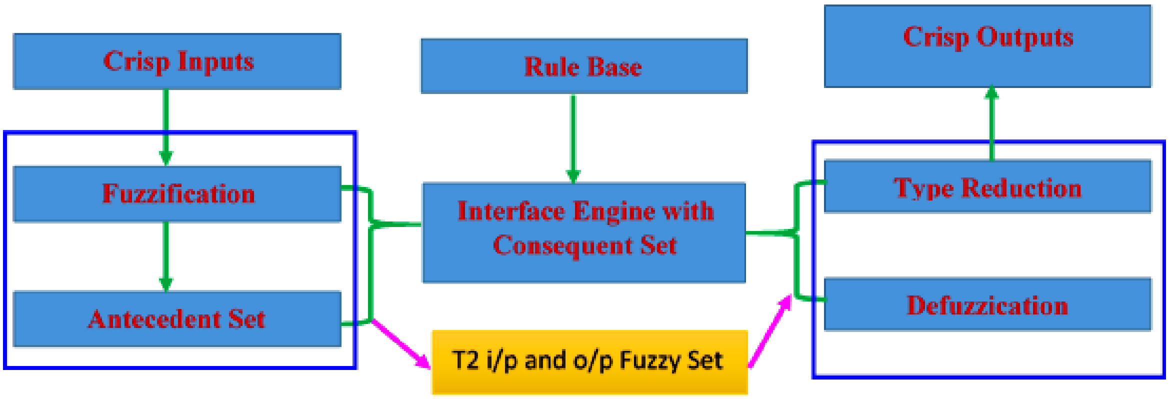


Figure 5.1: Implication model for type 2 fuzzy systems

data to attain complex decision results. The fuzzy sets presented here, let us model and reduced the effects of uncertainties.

Although, many type-2 fuzzy logic based methodology for mobile robot navigation have been describe in the chapter 2. Hagras [87] present a hierarchical type- 2 fuzzy logic control for mobile robot navigation in different unstructured environment. This paper describes the basic navigation behaviours of robot as well as coordination between these behaviours perform control decision. Baklouti and Alimi [88], deals with the design of an Interval Type-2 FLC for the navigation of mobile robots in unidentified and dynamic situations. The purpose of this controller is to perform the navigation in environments using polygonal robots from an initial point to a designed goal. In [89], the behaviour base control for mobile robot using type-2 fuzzy logic system was calculated. The method used in the creation of an algorithm, representing the straightforward behaviours of mobile robot.

Finally, the projected architecture using type-2 fuzzy logic can be easily implemented with low cost range sensor inside system. Further, experimental results show that, the control algorithm using type-2 fuzzy is efficient for localization, path planning and for navigation. In addition, results validate the algorithm source code for well working and the robot was able to successfully avoid obstacle in real world. Moreover, the knowledge based systems can provide more effective evaluation of suitability of decisions and learns from feedback. A representation of the inference model for type 2 fuzzy set systems is depicted in Fig 5.1.

The process initiates with fuzzification, when linguistic values inputted, and maps crisp points into type 2 fuzzy set systems. Further, fuzzification combines with antecedent set and enters into interface engine, at which inference engine computes the rule base by making logical mixtures of antecedent type 2 fuzzy set systems, whose results are concerned with consequent type 2 fuzzy systems to form an aggregate output type 2 fuzzy set. The type reduction (TR) collects all the output sets form interface engine and performs centroid calculation for combined type 2 fuzzy set. Further, this directed to a type 1 fuzzy set called type reduced set. Finally reduced set is defuzzified in order to obtain a crisp output [85, 142, 143]. The computational density of this model is condensed by interval type 2 fuzzy sets. It is suitable in the framework of hardware implementation in order to make easier the computational effort and speed up the inference time. Accordingly, type 2 fuzzy logic systems have been developed in fields like robotics, communication system and control systems among others [144–146]. Applications related to control algorithm and robotics are one of the most widely used fields of fuzzy logic. Type-2 fuzzy logic controller's advantages over type-1 fuzzy logic controllers (T1-FLC) have also been demonstrated and documented in [141].

5.2 Interval Type-2 Fuzzy Systems

Type 1 fuzzy system was firstly introduced by Zadeh [84] and later has been successfully applied in various fields such modelling, control, data mining, time-series prediction, linguistic summarization, and computing with words. The success of type 1 fuzzy logic control structure is mainly due to their capability to deal with knowledge-represented in a linguistic form instead of representation in the conservative mathematical structure. Accordingly control engineers have traditional relied on mathematical model for their design. However, we know that, the more complex a system, the less efficiency the model with membership functions. This is the fundamental concern that offer the motivation towards type 2 fuzzy logic.

A type 1 fuzzy system 'F' is incorporated with domain 'D_F' of real numbers (also called the universe of discourse of 'U') together with a membership function (MF) μ_F : DF $\rightarrow$ [0,1], i.e.,

The universe of discourse can be calculated using the following equation:

$$F = \int_{D_F} \mu(x)/x \tag{5.1}$$

For a discrete universe it is calculated by,

$$F = \sum_{x \in D_F} \mu_F(x)/x \tag{5.2}$$

Here '$\int$' denotes the collection of points for continuous system '$x \in D_F$' with associated membership grade $\mu_F(x)$. In malice of this, research has shown that there are restrictions in the ability of type 1 fuzzy system to model and minimize the effect of uncertainties.

Through the probability principle, the variance endows a measure of expansion about the mean and captures additional information about the probabilistic uncertainty. Type-2 FL endows this measure of expansion. It is the fundamental stage to the design of systems that include linguistic uncertainties and further translate into rule or input uncertainties. Random and linguistic uncertainties "flow" through a T-2 FLS. All these properties can be calculated using; firstly to defuzzified output and finally by the type-reduced output of that system (process given in Fig. 5.1). The type-reduced stage delivers a measure of diffusion about the defuzzified output of linguistic confidence interval. The type reduction stage depends upon linguistic or random uncertainties. If linguistic or random uncertainties increases then it also increases [141]. By modelling and minimizing their effects Interval type-2 fuzzy logic handles uncertainties. Type-2 FL is reduced to Type-1 FL if all uncertainties disappear and this is done by type reduction after defuzzification. Later, Type-1 fuzzy set transform into a Type-0 fuzzy set through difuzzyfier. The T-2 fuzzy logic set (FLS) is more suitable for difficult application in which we can't determine an exact membership function for a fuzzy set. Its other application is handle rule uncertainties and even measurement uncertainties.

Compare to Type-1 fuzzy logic set, Type-2 fuzzy logic set has more DOF for designed algorithm and this is due to presence of more linguistic parameters at type 2 fuzzy sets than Type-1 fuzzy sets. This indicates Type-2 fuzzy logic set can have superior performance rather than Type-1 fuzzy logic set. Although, it has no any mathematical proof which shows T-2 fuzzy logic set obtained better results for every applications; compare with T-1 fuzzy logic set. This can also be stretched to multi-sensor data fusion (MSDN) and further decision fusion approaches based on fuzzy logic. Membership function for the IT-2 fuzzy presented in fig 5.2.

The membership function is not just a value but a range or interval unlike type 1 fuzzy controller. In the Fig. 5.2 the upper limit of the membership function is given by 'ξ'

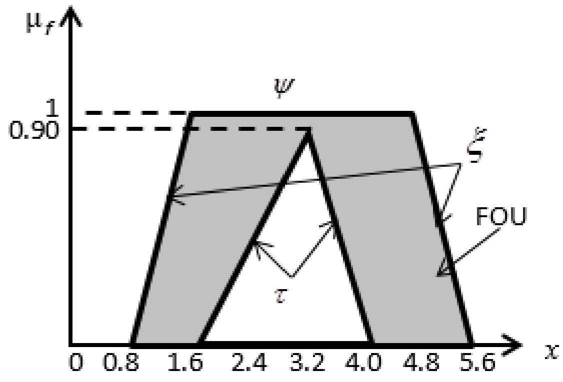


Figure 5.2: Membership function for interval Type-2 fuzzy logic

whereas the lower limit is given by 'τ'. The area between both these limits is called the footprint of uncertainty or FOU.

5.3 Interval Type 2 Fuzzy Logic Controllers

The representation in a logic of diagram of an interval type 2 fuzzy logic controller is similar to its type 1 pattern. The major difference is that at least one of the fuzzy systems in the rule base is an interval type 2 fuzzy system. Therefore, the outputs generated through the inference engine are interval type 2 fuzzy systems, and a type reducer is required to transform them into a type 1 fuzzy system prior to the defuzzification.

The inputs given to the controller are stated as; left obstacle distance (LOD), right obstacle distance (ROD), front obstacle distance (FOD) and target angle (SA) whereas velocity of left wheel (VLW) and velocity of right wheel (VRW) are outputs from controller. Accordingly, the computation for one of the inputs LOD is shown. The same process is repeated for all the inputs to receive the output.

$R^n : IF x_1\ is\ \psi_1^n$ and $\ldots x_k\ is\ \psi_k^n$, THEN y is $Y^n,\ n = 1,2,\ldots N$

Where,ψ_k^n are IT2 FS and $Y^n = [(y^{\xi})^n, (y^{\tau})^n$ is an interval, which can be represent the centroid of an IT 2 FCS. Assume the input vector is LOD, FOD, ROD =(LOD_{1-k}, FOD_{1-k}, ROD_{1-k} and TA for consecutive point).

Typical computations in an interval type 2 fuzzy logic system involve the following steps:

- Compute the membership of LOD_k on each LOD_k = 1, 2, ..., k, n = 1, 2, ...,N.
- Compute the firing interval of the n^{th} rule, $F_n(LOD)$ using the formula:

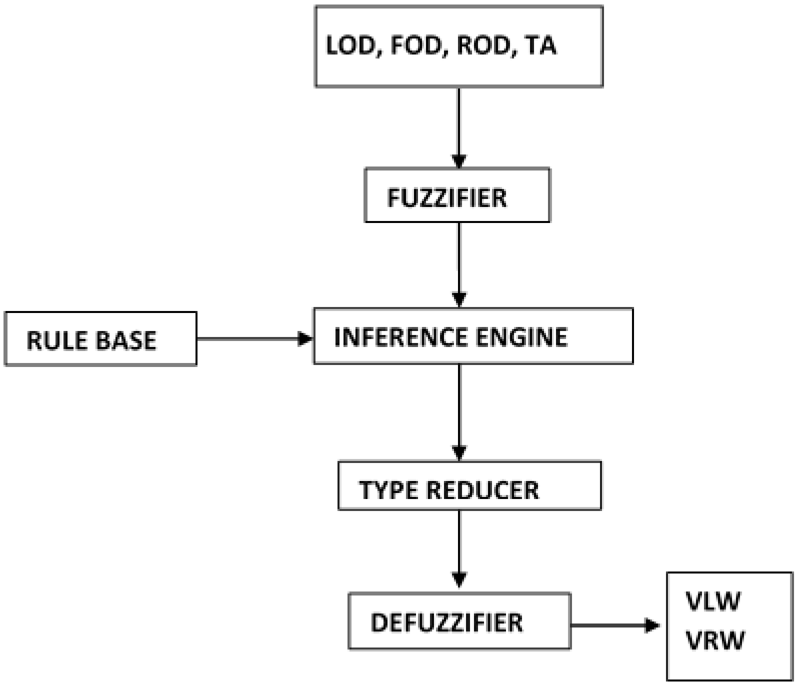


Figure 5.3: Flowchart for type-2 fuzzy controller

$$F^n(x') = [\mu_{\tau_1^n}(x_1')X.....X\,\mu_{\tau_I^n}(x_I'),,,\mu_{\xi_1^n}(x_1')X.....X\,\mu_{\xi_I^n}(x_I')] = [f_\tau^n, f_\xi^n], n = 1,2,.....N \quad (5.3)$$

- Perform type-reduction to combine $F_n(LOD)$ and the corresponding rule consequents. There are many such methods. The most commonly used one is the center-of-sets type-reducer whose formula is given by,

$$Y_{\cos(x')} = \bigcup_{\substack{f^n \in F^n(x') \\ y^n \in Y^n}} \frac{\sum_{n=1}^{N} f^n y^n}{\sum_{n=1}^{N} f^n} = [y_l, y_r] \quad (5.4)$$

5.4 Simulation

The robot was given a set of instructions to follow and the program has been written on WEBOTS simulator platform. The microchip in the robot was imparted with the program written in the WEBOTS simulator. Various obstacles were provided in the path of the robot so that it had to change its path to reach its destination. Fig. 5.4 is showing the arrangement of the obstacles inside environment. The robot can be seen as a blue structure at the origin of the graph whereas the destination is seen as the ball at the other end of the graph. The robot has to escape the obstacles and reach the destination. The program allows the robot

Table 5.1: Overall path length, time taken and errors between results

Algorithm	TSR (P)*	ESR (P)*	TSR (T)*	ESR (T)*	ERROR
T-2 FLC	*0.753*	*0.760*	*00:46:600*	*00:47:760*	*0.9210*

"TSR (P)" = Theoretical Simulation Result Related to Path Length (in meter).

"ESR (P)" = Experimental Simulation Result Related to Path Length (in meter).

"TSR (T)" = Theoretical Simulation Result Related to Time Taken (in minute).

"ESR (T)" = Experimental Simulation Result Related to Time Taken (in minute).

"ERRORS" = Between Path Length i.e. TSR and ESR

to reach the destination safely without colliding with the obstacles. Fig 5.5 shows the path of the robot taken to reach the destination.

5.5 Experimental Analysis

The path obtained by the robot throughout simulation was confirmed by implementing the program on a Hemisson robot in a physical environment analogous to the environment fashioned in simulation (Fig. 5.6). The path length of the robot was measured in the real environment as well as in the simulation.

5.6 Results and Discussion

Comparison between simulation and experimental results is quoted in Table 5.1. For comparison purpose, we target the length of the path taken by the robot during the navigation and also examine the time from starting point to termination point (given by table 5.1). From the table we observe that, error between experimental and simulation results are not much more. Therefore, the results from the proposed method is valid for the optimality.

5.7 Summary

For experimental and theoretical simulation analysis, we uses WEBOTS simulation software. From simulation results (Table. 5.1) it is found that the technique which has been used to optimize the path length and time is well compare to previous method. Using T-2

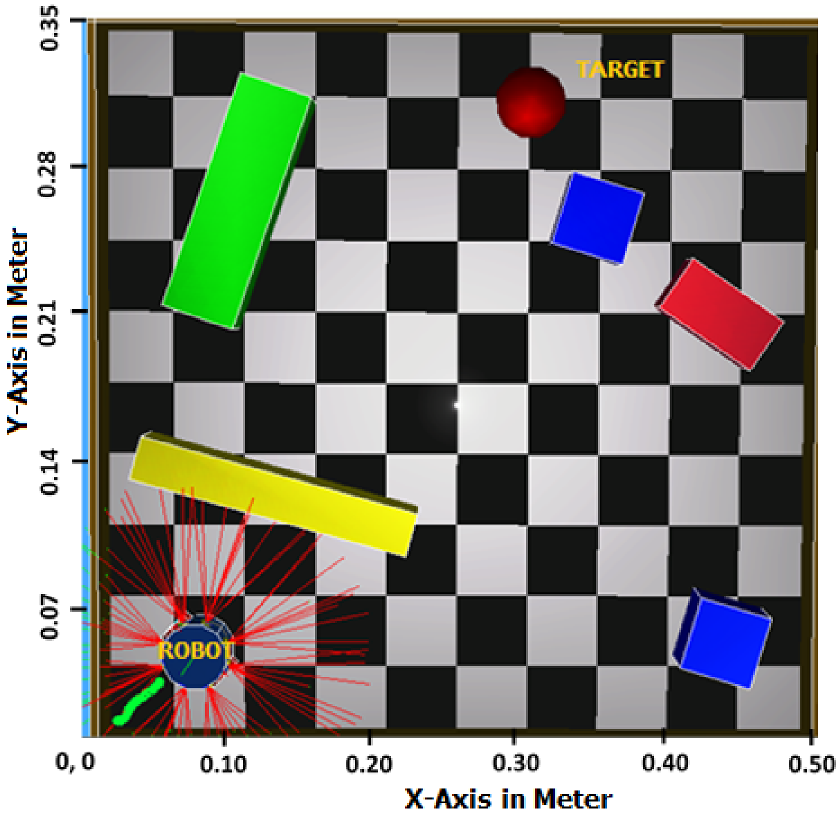


Figure 5.4: showing the obstacles posed in the robots path

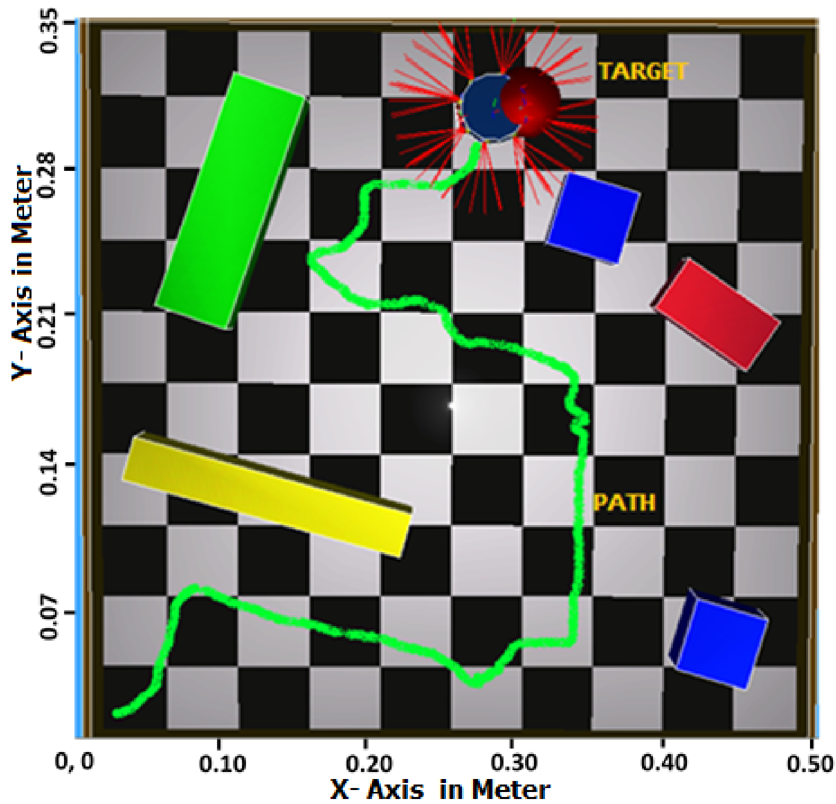


Figure 5.5: Path taken by the robot during simulation in Webots for type 2 fuzzy

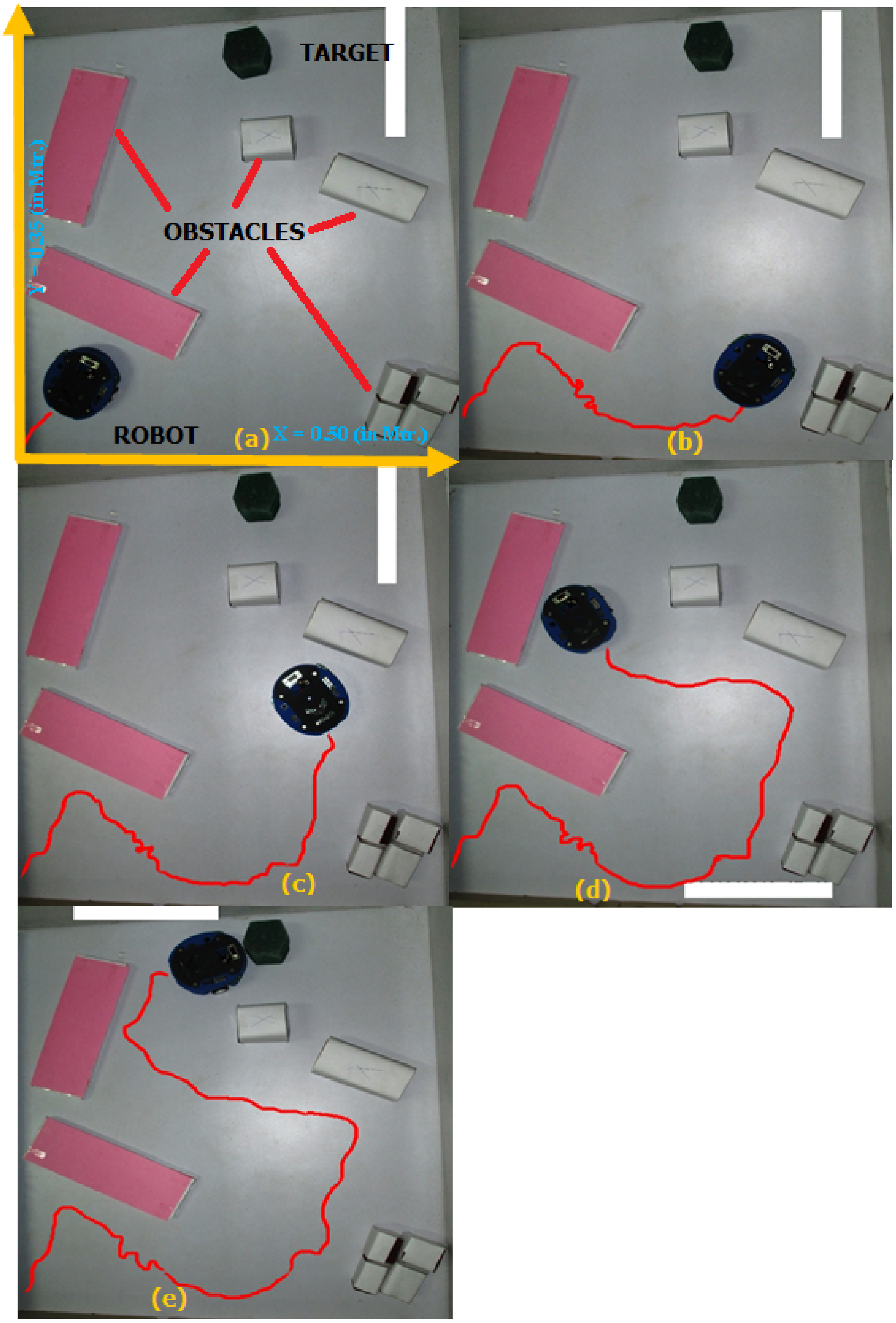


Figure 5.6: Path taken by the robot during experiment using Type-2 fuzzy controller

FLC the robot was successful in escaping the obstacles in the path and was successful in reaching the target point. Further, the comparison between simulation and experimental results showed a good agreement.

Chapter 6

Recurrent Neural Network (RNN) for Navigation

To control navigation strategies for mobile robot is most common area of research in robotics. In recent era, how to control the motion of mobile robot inside environment is the main attraction of research. To create collision free navigational path for mobile robot on working platform without human interaction recurrent neural network (RNN) techniques has been implemented based on sensory information i.e. information about path. RNN technique covers a continuum degree of technologies based on application. In this chapter, development and control of RNN system has been well defined. For theoretical and experimental analysis Webots simulation software is used.

6.1 Introduction

From last decade, requirements related to control unit of mobile robot is the essential concern. Accordingly, navigation and path planning have been studied extensively. To generate online map for path planning, sensor network has been used widely. Hence, robot move from one position to another and avoid obstacles on run time in effective manner. In addition, to conduct autonomous navigation on ambiguous environment, where stationary and moving obstacles (human, robots) co-exist, a mobile robot must be able to detect uncertainty at real time [95, 96]. The robot system must be employed with wheel encoders, sensor network, odometers and camera to detect nearby obstacles. This chapter delivers recurrent neural network (RNN) based learning methodology.

RNN approach [97–99] has been extensively used in recent years based on integrated map learning (integration of sensory). During the navigation, current position of the robot can be known continuously from sensor fusion, odometry and camera readings. During navigation, the mobile robot continues with significant navigation errors, which can be occurred due to equipment readings. Therefore, switching between local and global frames has been employed for a calibration purpose after odometry errors are accumulated. This methodology offers two advantages compared to other method. Primarily, the gathered odometry errors can be balanced and precious navigation may be achieved. Secondly, if sensor fusion is not achieved, robot navigation remains without a disturbance under the calibrated local coordinate frame for a short distance.

6.2 Analysis of Related Work

In the area of robotics, researchers have been contributed essential interest in the part related to autonomy of robots as well as its flexibility in different environment and constraints. To solve related problem different methods has been used. The success of any projecting system depends on its efficiency and effectiveness of the solution, after implementation in real world. Researchers conduct various investigations to improve robot autonomy; accordingly. Today control projects have been developed widely.

In particular, recurrent neural network RNN is a dynamic part of neural network, which involves both methodology of feed forward and feedback network [100]. RNN mainly used to optimize the control problem. Recently, many robotics projects have used RNN to develop suitable control systems and optimize the navigation map [102, 103]. Localization problem related to mobile robot is the estimation of robot's location and orientation comparative to its environment. Moreover, to develop the control algorithms, which has ability to create collision free path (to follow obstacle avoidance behavior) [105, 106, 132]; is the module of advanced robotics control systems.

6.3 Real Time Learning "RNN Algorithm"

The algorithm is based on combination both principal i.e. feedback and feed forward. For training a neural network to execute any task, weights of each unit must be changed in such a way that the difference between the desired output and the actual output is reduced. It is required that the neural network computes the error offshoot of the weights (EW). In other

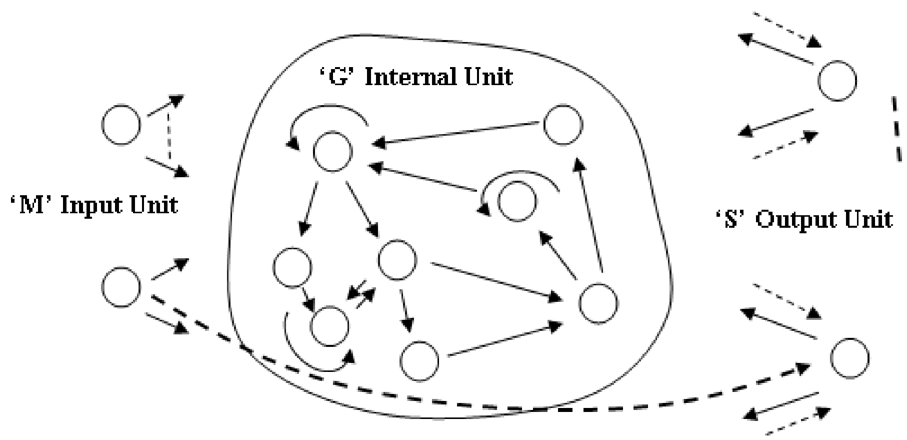


Figure 6.1: The basic network architecture used for RNN. Dotted arrows mark presents trained condition

words, it must calculate the fluctuation of error occurring with a slight increase or decrease in each weight.

The time learning algorithm is easiest to comprehend if all the units in the network are linear. The algorithm computes each *EW* by first determining the activation, the rate at which the error varies as the movement level of a unit is altered. For output units, the activation error is just the difference between the real and the desired output. To calculate this for a hidden unit in the layer just before the output layer, firstly all the weights amongst that hidden unit and output units to which it is linked are recognized.

Activation errors of those output units are computed and the products are added. This sum equals the activation error in the hidden layer penultimate to output layer. The activation for other layers can also be computed in the reverse direction through the network. Once the activation error has been computed for a unit, it is simple to calculate the *EW* for each incoming link of the unit. The *EW* is the creation of the *EA* and the activity through the incoming link.

For the RNN, here only consider a particular kind of discrete time models without spatial organization. In this model 'M' is the number of input with an activation vector. 'G' represents the internal unit of network and 'S' represents the output of the unit as a velocity of wheel.

After considering input vector (*M*) the mathematical model of the input can be given as following:

$$u(n) = (u_1(n), ..., u_M(n))^T \tag{6.1}$$

Similarly, for internal (G) and for output (S) is:

$$x(n) = (x_1(n), ..., x_G(n))^T \tag{6.2}$$

and,

$$y(n) = (y_1(n), ..., y_S(n))^T \tag{6.3}$$

Where, 'T' denotes the transpose.

Now, the weight matrices for input, internal and output connection are collected as;

$$W^{in} = \left(w_{ij}^{in}\right) \tag{6.4}$$

$$W = \left(w_{ij}\right) \tag{6.5}$$

and,

$$W^{out} = \left(w_{ij}^{out}\right) \tag{6.6}$$

Further, a zero weight value can be interpreted as "no connection".

The activation of internal units (G) is updated according to,

$$x(n+1) = f\left(W^{in}u(n+1) + Wx(n) + W^{back}y(n)\right) \tag{6.7}$$

Where, "u (n+1)" is the external given input and 'f' denotes the activation function.

The output is computed according to,

$$y(n+1) = f^{out}\left(W^{out}(u(n+1), x(n+1))\right) \tag{6.8}$$

Where, "u (n+1), x (n+1)" denotes input and internal activation vectors respectively. Now, the derivative of an internal and output unit with respect to time a weight W_{kl} is given by,

$$\frac{\partial v_i(n)}{\partial w_{kl}} = f'(z_i(n)) \left[\left(\sum_{j=i}^{G+S} w_{ij} \frac{\partial v_j(n)}{\partial w_{kl}} \right) + \partial_{ik} v_l(n) \right] \tag{6.9}$$

Where k,l G+L+K, $Z_i(n)$ is again the unit's potential, but $\delta_{ik} v_l(n)$ represents an explicit effect of the weight w_{kl}.

The equation no.6.9. , for each internal or output unit constitutes an G+S-dimensional discrete-time linear system with time-varying coefficients, where

$$\left(\frac{\partial v_1}{\partial w_{kl}}, \ldots\ldots., \frac{\partial v_{G+S}}{\partial w_{kl}} \right) \tag{6.10}$$

Now initialize 'equation 6.9' and calculate the error gradient as follow;

$$\frac{\partial E}{\partial w_{kl}} = 2 \sum_{n=1}^{T} \sum_{i=G}^{G+S} (v_i(n) - d_i(n)) \frac{\partial v_j(n)}{\partial w_{kl}} \tag{6.11}$$

So, updating the each weight after a complication of iteration of presenting all training data by;

$$w_{kl} = w_{kl} - \gamma \frac{\partial E}{\partial w_{kl}} \tag{6.12}$$

Where, γ is a learning rate.

$$w_{kl}(n+1) = w_{kl}(n) - \gamma \sum_{i=1}^{S} (v_i(n) - d_i(n)) \frac{\partial v_j(n)}{\partial w_{kl}} \tag{6.13}$$

Where assume W_{kl} is a constant, not a dynamical variable, in deriving (6.9), so we have to keep the learning rate small enough. Equation (6.13) is referred to as real time recurrent learning.

6.4 Experimental Results and Discussion

At each interval, infrared sensors S1, S2, S3, S4 and S5 provides the obstacle distances as well as environmental information and based on these information (after sensor fusion and integration) robot construct its navigational path. We consider values only; which are less than or equal to 10 cm for analysis of shortest and perfect path. In order to find the possibility of path the value greater than 10 cm stated as '0' and '1' if less than. On the other hand, if robot navigates towards the goal, at the same time classification of obstacle situation that may disturb the movement of robot has been made "Fig. 6.2, 6.3 and 6.4".

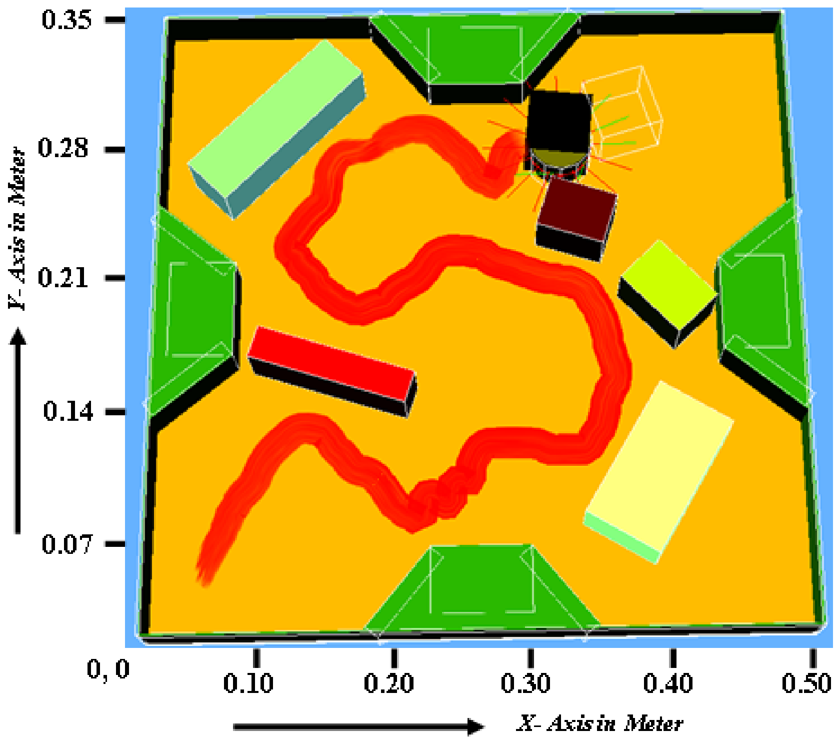


Figure 6.2: Overall configuration of the model

The output trajectory towards target 'S = [T1 T2 T3 T4]' for different states, which signifies the seven possible states and avoid the obstacles as shown in "Fig. 6.2, 6.3 and 6.4". If the robot does not receive any signals from its sensory part during movement; then, we say that route is clean; free navigation possible. Now, addition of another output i.e. 'T5' activate the free path and robot decides itself to move forward. Target achieving provides eight outputs for different environmental conditions; therefore all are presented as single function:

F = 0: free path T5 activated, F = 1: Output T1 activated, F = 2: Output T2 activated, F = 3: Output T3 activated, F = 4: Output T4 activated. Fig. 6.4 represents the various situation of obstacle avoidance during learning. This Fig represent the activation of an algorithm according to obstacle and target position using RNN based on real time learning algorithm.

6.4.1 Simulation Result

To describe in detail, firstly the robot receives its target coordinates inside environment and clarify its actual position in these directional frame i.e. O, x, and y. After that localizes the

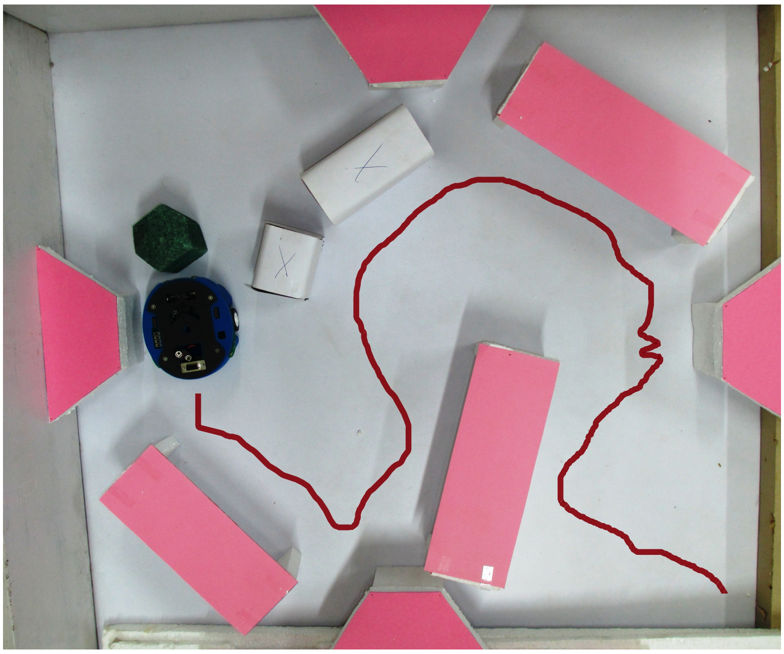


Figure 6.3: Obstacle detection and path planning by mobile robot

environment conditions such as neighbour obstacles, wall and other uncertainty with the help of sensors and camera.

To predict the next movement stage, sensor fusion delivers the perfect data after integration. Similarly, the robot drafts its path confidence according to integrated data; two feasible cases calculated. First one, if the sensors data indicates obstacles are present in the path, at the same time obstacle avoidance algorithm is activated to create collision free path; otherwise the robot continues its motion unless the target is not reached. After each period of certain time, the robot updates its position (coordinate) using the localization algorithm. Finally stop condition is arising for mobile robot. Condition is, if the distance between robot and target is less than or equal to 2 cm; implies that robot follow the stop condition. This approach is well developed on Webots simulation platform including different obstacle conditions "Fig. 6.2 and 6.3".

With reference to environment, the safe and perfect path searching by robot towards target depends upon execution of precious motion at different location with different moment. Consequently, robot performs different tasks with reference to position of the obstacle such as front obstacle-turn left or right according to target, back obstacle-free movement, turn right and left-if obstacle (robot and human) in motion.

The proposed algorithm performs our tasks with different stages or simply says, algorithms

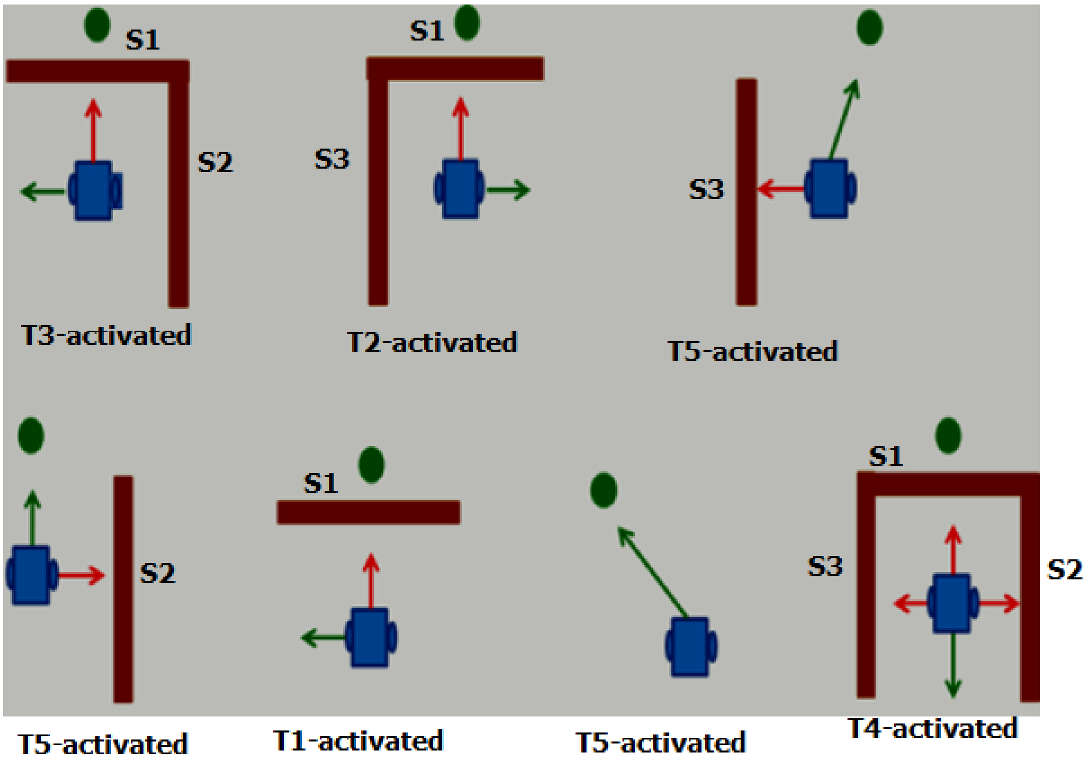


Figure 6.4: Various situation of obstacle avoidance during learning

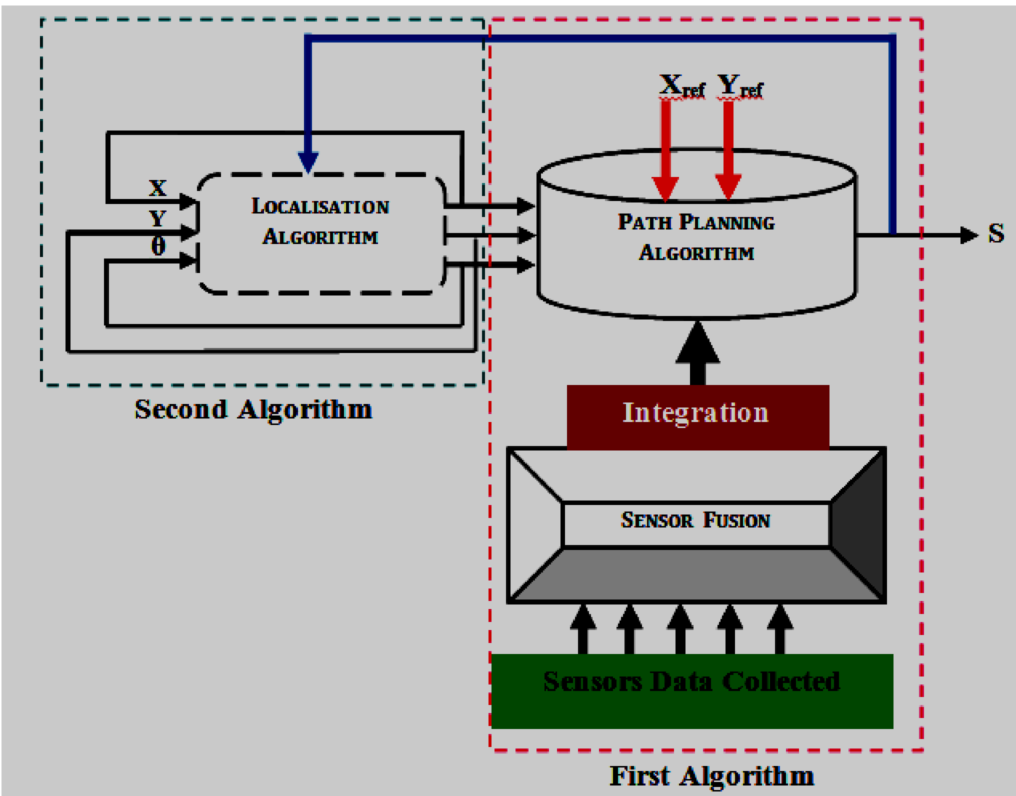


Figure 6.5: Architecture of the control algorithm for erection of navigation strategies

divided into two sub-algorithms to perform tasks and presented by "Fig. 6.5": First is path planning algorithm that uses the target coordinates 'X_{ref}','Y_{ref}' and the current coordinates of the robot (X, Y, θ) and second is the localization algorithm. Both algorithms solve using intelligent technique and first learning algorithm results depend upon second one.

6.5 Localization Using RNN

The proposed work is based on combined effect of localization with recurrent neural network (RNN). This thesis explores; how to plans mobile robot to predict its position periodically using odometry system as well as how to updates its coordinates systems.

The RNN is implemented for path planning and navigation after sensor fusion as well as updates its navigation map according to sensor data. In addition, 'Se' stands and includes the sampling data for further reference and express robot configuration in the Cartesian coordinates system (O, x, y) based on rotational principle.

In fact, the robot calculates its future or current configuration with reference to previously position and navigation action. Indeed, RNN stands for position parameters (X,Y,θ) and work already executed by the robot as the output 'S'. Accordingly, the network provides the new configuration to the robot (X, Y, θ), depends upon previous network. After that, combined all network to evaluate the final output as presented in 'Fig. 6.5, 6.6 and 6.7'. In addition, hyperbolic tangent sigmoid transfer function is used for the hidden layer and linear transfer function used for the output layer. According to the means squared errors, measurement of the network's performance has been done well "Fig. 6.7". Four neurons are chosen for hidden layer. At the time of training phase navigation, significant improvement has been considered with robot movement and it is all about due to communication with RNN over simply neural network. Finally, the fixed architecture with different data of RNN and the outputs of test phase has been represented by "Fig. 6.6 and 6.7". In this Fig straight line represents the desire position at each interval. Including four inputs for path planning (i.e. 'X-X_{ref}','Y-Y_{ref}', 'θ' and function of obstacles 'F' and one RNN output (i.e. 'S') the overall RNN processes has been projected. With RNN, after setting the weights and preferences; system tested with different base. "Fig. 6.6 and 6.7" represents the result of MSE for test phase of RNN with curves.

If the distance increases as well as many changes has been made with direction of

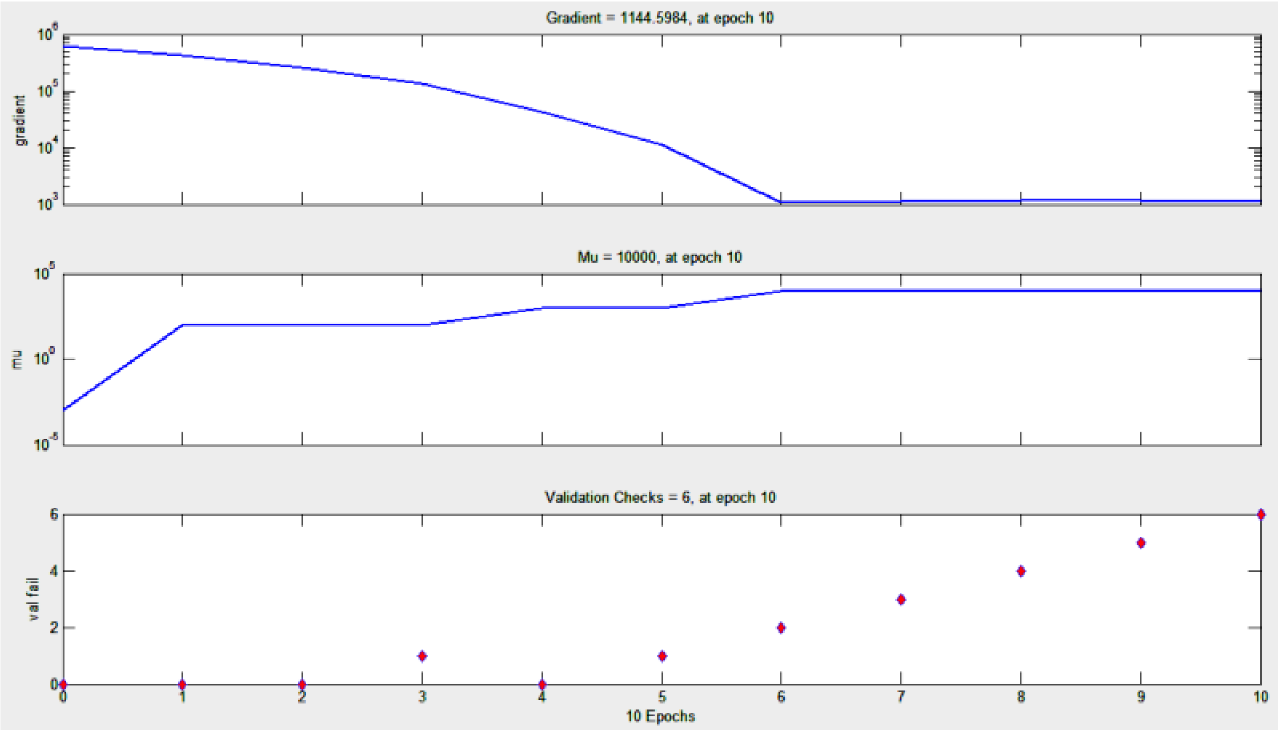


Figure 6.6: Value in test phase

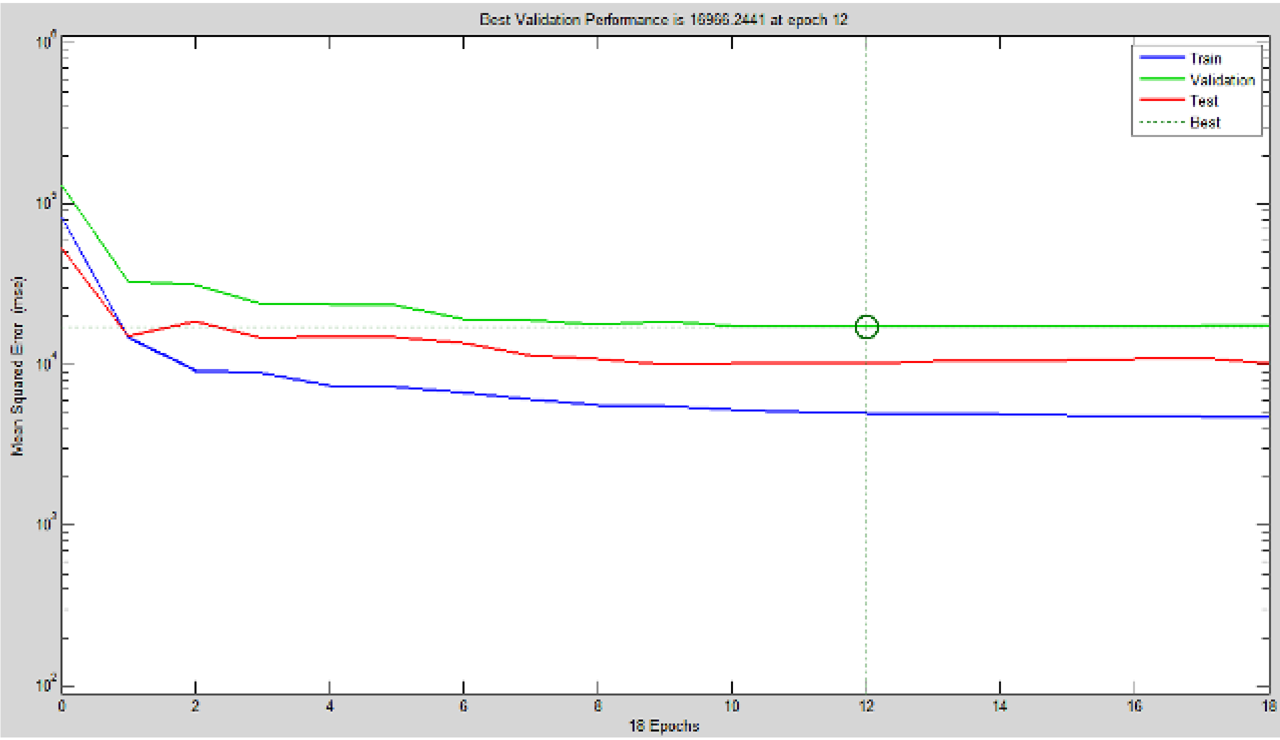


Figure 6.7: Curves represent the errors of train (blue line), validation (green line), test (red line) and best (dotted line) data

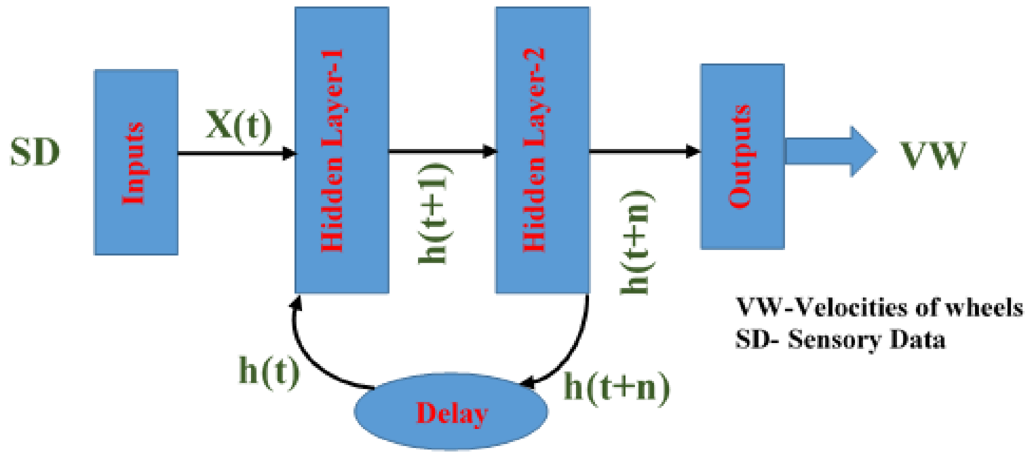


Figure 6.8: Multilayer RNN for implementation of robotic behaviours

the mobile robot, at that time inaccuracy of the robot configuration substantially increases the inaccuracy due to cumulative errors, which created during the integration of different elements with displacement of robot. Accordingly, the use of time learning methodology reduces these types of errors and learning creation achieve preciously by robot.

The whole process of RNN is represented by Fig. 6.8. In this Fig, first layer is used as input layer at which four neurons (LOD = Left obstacle distance, FOD = Front obstacle distance, ROD = Right obstacle distance and T.A = Target Angle) are combined with the network with individual sensors data (S1, S2.). Then, the robot network contains two hidden layers as shown in Fig 6.8 which tune the weight of neuron; as with one hidden layer it is difficult to train the network within a definite error limit. The training error has been defined as the variation between desired output and real output. From above Fig, there are two hidden layers where first hidden layer has eighteen neurons and the second one has five neurons. Finally, an output layer is generated with a single neuron which provide steering angle to control the direction of movement of the mobile robot. Real time recurrent learning method is used to decrease the error and improve the path at time of online navigation towards target point.

Table 6.1 represents the simulation results for robot navigation using RNN technique. The errors between experimental and theoretical path analysis with respect to time also presented.

Table 6.1: Overall path length, time taken and errors between results

Algorithm	TSR (P)*	ESR (P)*	TSR (T)*	ESR (T)*	ERROR
FLC	*0.739*	*0.745*	*00:28:192*	*00:28:876*	*0.8053*

"TSR (P)" = Theoretical Simulation Result Related to Path Length (in meter).

"ESR (P)" = Experimental Simulation Result Related to Path Length (in meter).

"TSR (T)" = Theoretical Simulation Result Related to Time Taken (in minute).

"ESR (T)" = Experimental Simulation Result Related to Time Taken (in minute).

"ERRORS" = Between Path Length i.e. TSR and ESR

6.6 Summary

This investigation is based on RNN for path planning as well as development of autonomous navigation learning algorithm for a mobile robot, functioning in a known and partially unknown environment in presence of obstacles. Firstly, we learnt obstacle avoidance algorithm and secondly developed the localization technique for mobile robot navigation, which is essential stage for development of path planning algorithm. In addition, obstacle avoidance algorithm plays an important role while mobile robot developing the collision free path. To control the robot, two integrated RNNs algorithm are developed and both are connected in series. Environmental map develop by robot depends upon sensor fusion and learning of RNN. The advantage of RNN based methodology is that, it can't require any heavy mathematical model. The robot motion depends upon RNN network which is connected in series and integrated over time to time. In this chapter, firstly RNN helps to develop the localization technique after that, embedded for path planning. As a result, the developed intelligent algorithm offers the mobile robot to construct its collision free path as well as robot able to find its target in an environment. In addition, the developed algorithm is easy to implement in realistic world. Finally, it offers abundant capability to the robot, to estimate its position inside environment with precious rate and attain target in efficient manner.

Chapter 7

HARDWARE ANALYSIS

The Hemisson is a cheap mobile robot which has been principally developed for the requirements of research institute. Hemisson has attractive features for students and researchers in any science and engineering institute.

7.1 Introduction

Two Differential drive motors has been engage with robot system. Motors are receiving data from eight IR (Infrared) light and distance sensors mounted on the robot body. CeeBot-Hemisson communicates with computer through a serial RS-232 interface or via Bluetooth. Required programming can be done with CCS C compiler and also can be downloaded in controller of robot by the serial port using the Hemisson Uploader. Other equipment's include programmable LED, buzzer and switches. The Hemisson robot equipped with 8bit microcontroller unit.

7.2 Specification of the Robot

* **Processor** [*PIC16F877 (20MHz CPU clock, 8bit, 8K words program memory)*]
* **Motors** [*2 DC motors to drive independently both wheels. Zero turning radius.*]
* **Sensors** [*8 ambient light sensors (infrared). 6 obstacle detection sensors(infrared). 2 line detection sensors.*]
* **Battery** [*1 connector for a standard 9V battery.*]

Figure 7.1: Top view and side view of Hemisson Robot

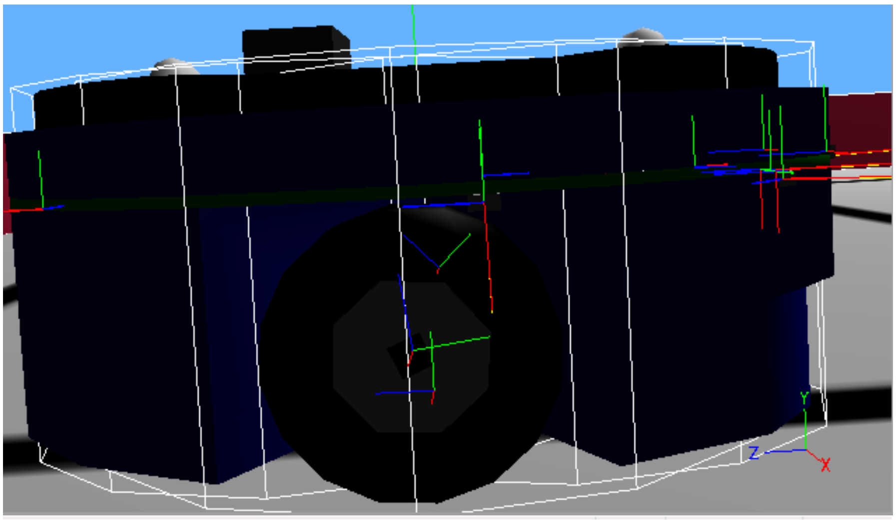


Figure 7.2: Side view of Hemisson Robot on simulation platform

* **I/O Interface** [*1 serial port for communication with computer (DB9 connector). 1 TV remote receiver. 1 Buzzer. 4 LEDs. 4 Programmable Switches.*]
* **Extensions** [*1 extension bus for additional modules. 1 slot for a felt pen in the centre of the robot.*]
* **Size** [*12cm (4.7") diameter.*]
* **Weight** [*200g*]

These are pictures of the Hemisson robot (Fig. 7.1 and Fig. 7.2).

Figure 7.3: General Accessories of Hemisson Robot

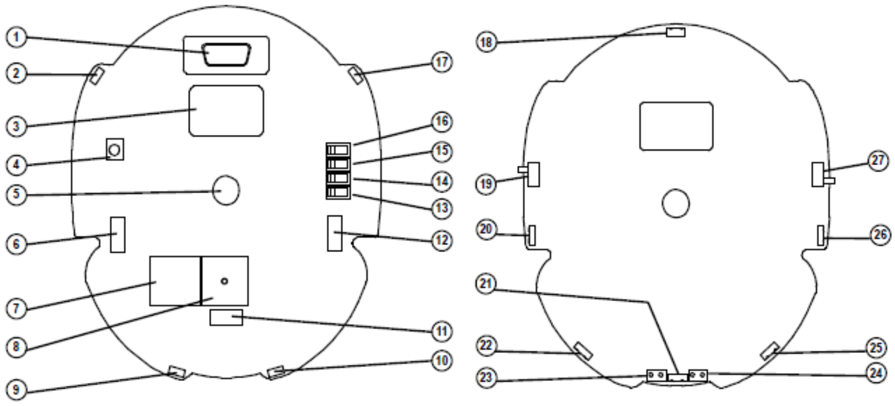


Figure 7.4: Views of the Hemisson Robot

1: RS232 connector
2: Pgm/Exec LED
3: Battery Location
4: IR Remote receiver
5: Felt-Pen Location
6: Extension Bus (A)
7: Microprocessor
8: Buzzer
9: Front Right LED
10: Front Left LED
11: Extension Bus (B)
12: Extension Bus (C)
13: Switch 4
14: Switch 3
15: Switch 2
16: Switch 1
17: On/O_ LED
18: Rear sensor
19: Switch On/O_
20: Left sensor
21: Front sensor
22: Front-Left sensor
23: Left Ground Sensor
24: Right Ground Sensor
25: Front-Right Sensor
26: Right Sensor
27: Prog/Exec Switch

7.3 Summary

In this chapter detail specification of experimental robot is given. This robot is used for experimental analysis.

Chapter 8

RESULTS AND DISCUSSION

With the current findings, a problem related to directional path analysis of mobile robot in several environments has been examined. As per kinematical feature, AI techniques (e.g. Fuzzy Logic, T2-FLC, and Recurrent Neural Network) have been implemented to optimize the path and creat the collision-free motion.

To maintain expertise in performance, self-adaptive mobile robot navigation, localization algorithm and path planning algorithm should be compatible with the kinematics structure of the robot. To provide vehicle's configuration through sensory statistics is not possible, so it becomes necessity to attain stable kinematic prototype in nature for the mobile robot in its global and local reference frame, respectively.

In the third chapter, kinematic study of mechanical structures of a mobile robot has been presented regarding the description of the motion with reference to a fixed reference cartesian frame. In addition, the forces and moments that causes motion of the structure is not considered. Further, modelling of mobile robot is completed by merging all kinematic constraints for separate wheels. The different stages of designing wheeled mobile robot has been performed as: positioning of the robot inside environment, analysis of maneuverability and holonomicity checking with reference to kinematic constraints and generalized control of developed kinematic model. The maneuverability is equivalent to control the degrees of freedom that the robot may follow during final configuration of motion towards target. Modelling of mobile robot with differential drive wheels has been addressed with a differential geometric point of view. Considering only the conventional theory of "pure rolling without slipping"; a robot can rotate on the centre position (higher pair contact) only if the angular velocities of the two wheels configuration are equal and opposite in nature.

Navigational study related to mobile agent involves various critical troubles in real

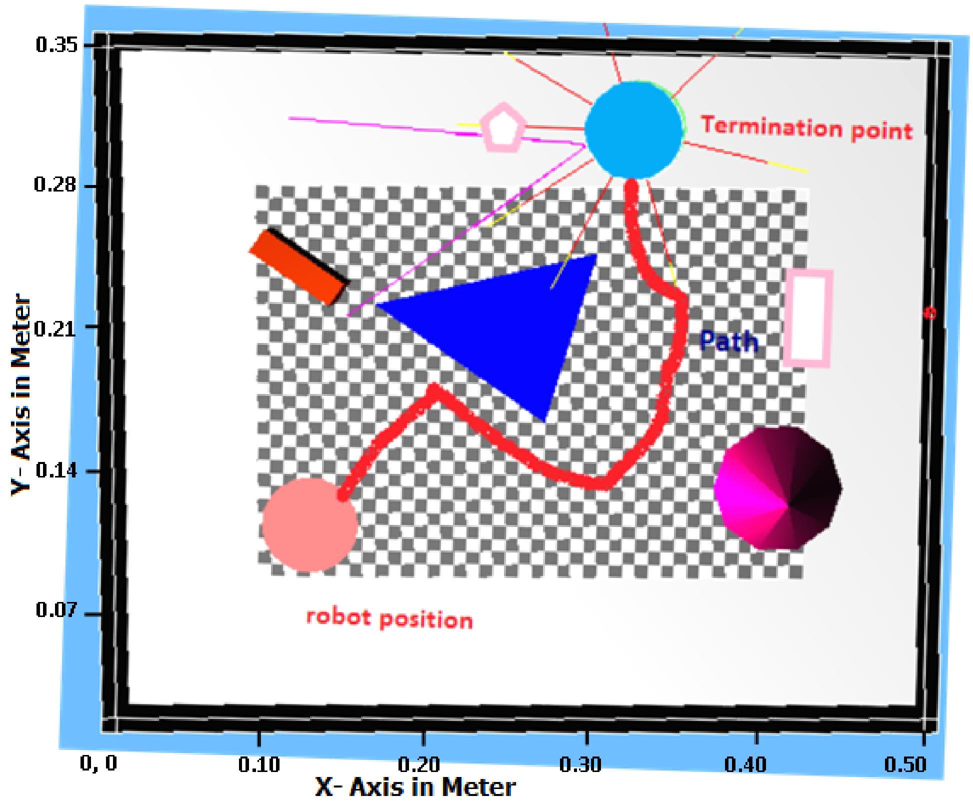


Figure 8.1: Path taken by the robot during simulation in WEBOTS for Fuzzy logic

world environment than the problems concerning kinematic instability (due to mechanical imperfection in design) of the robot configuration. In addition, to select the suitable navigational techniques in the field of mobile robotics research is much more important. The all forms of robotic behavior for the collision free navigation path depend on intelligence of the controller.

Fuzzy navigation method, which can deliver a sensitive control for mobile robot to move in a reasonable direction and velocity maneuvers of the autonomous mobile robot, is stimulated to attain reasonable communication in static environments. A Fuzzy logic controller (FLC) has been recognised with the model due to more compatible with the reasoning process of human behaviours. Fuzzy behaviour-based design for mobile robot navigation in known or partially unknown environments incorporates design of rule base as basic behaviours for mobile robot navigation, i.e., goal seeking, wall following, obstacle avoidance and deadlock disarming etc.

Navigation of the robot with different environment has been shown in this chapter to check the results. The Fig 8.1 shows the navigation of the mobile robot inside Webots sim-

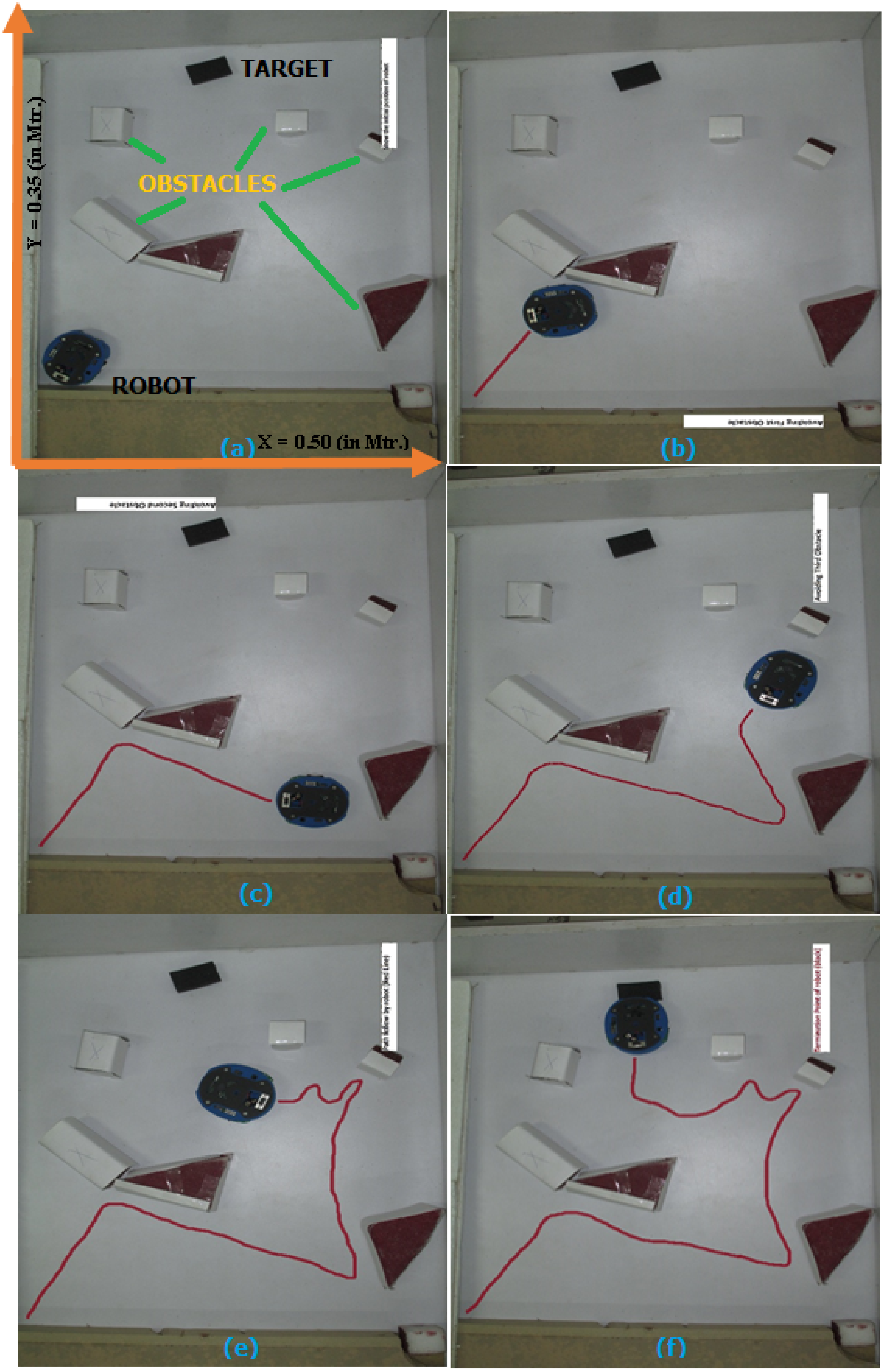


Figure 8.2: Path taken by the robot during experiment using Fuzzy controller

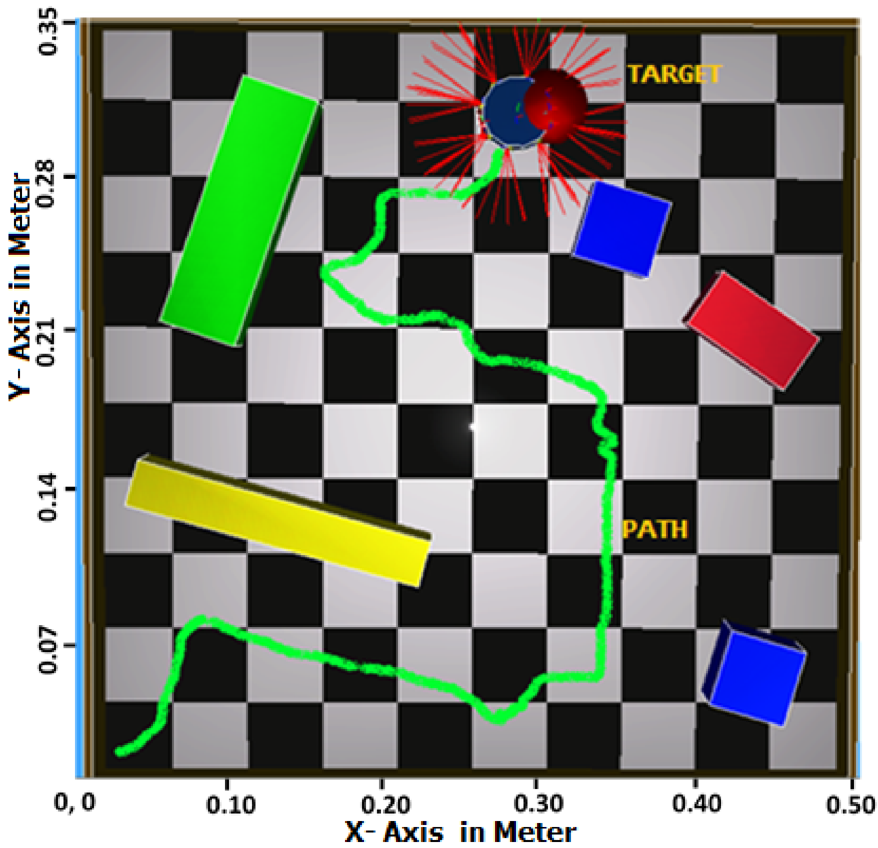


Figure 8.3: Path taken by the robot during simulation in WEBOTS for type-2 fuzzy

ulated world as well as Fig 8.2 present the experimental analysis using the fuzzy controller.

In the next section advanced form of fuzzy logic behaviour has been presented which is based on interval type-2 fuzzy principle. This improved behavioural logic allows us to eliminate more uncertainties from the decision making process. The above statement is validated through the number of simulation conducted on Webots platform using type-2 fuzzy mechanism. The truth can also be confirmed by comparing the navigation of the robot in different environment using the algorithm. The Fig 8.3 shows the navigation of the mobile robot in different simulated environment as well as Fig 8.4 shows the experimental analysis using the type-2 fuzzy logic control mechanism.

The multilayer feedback and feed forward recurrent neural network using the principle of back propagation through time learning algorithm has been engaged in the subsequent chapter to increase the accuracy in steering angle measurement by removing uncertainties in target sensor reading. Consequently, 250 training pattern are used for designing an intelligent well trained RNN controller for mobile robot which can be used to navigate in a

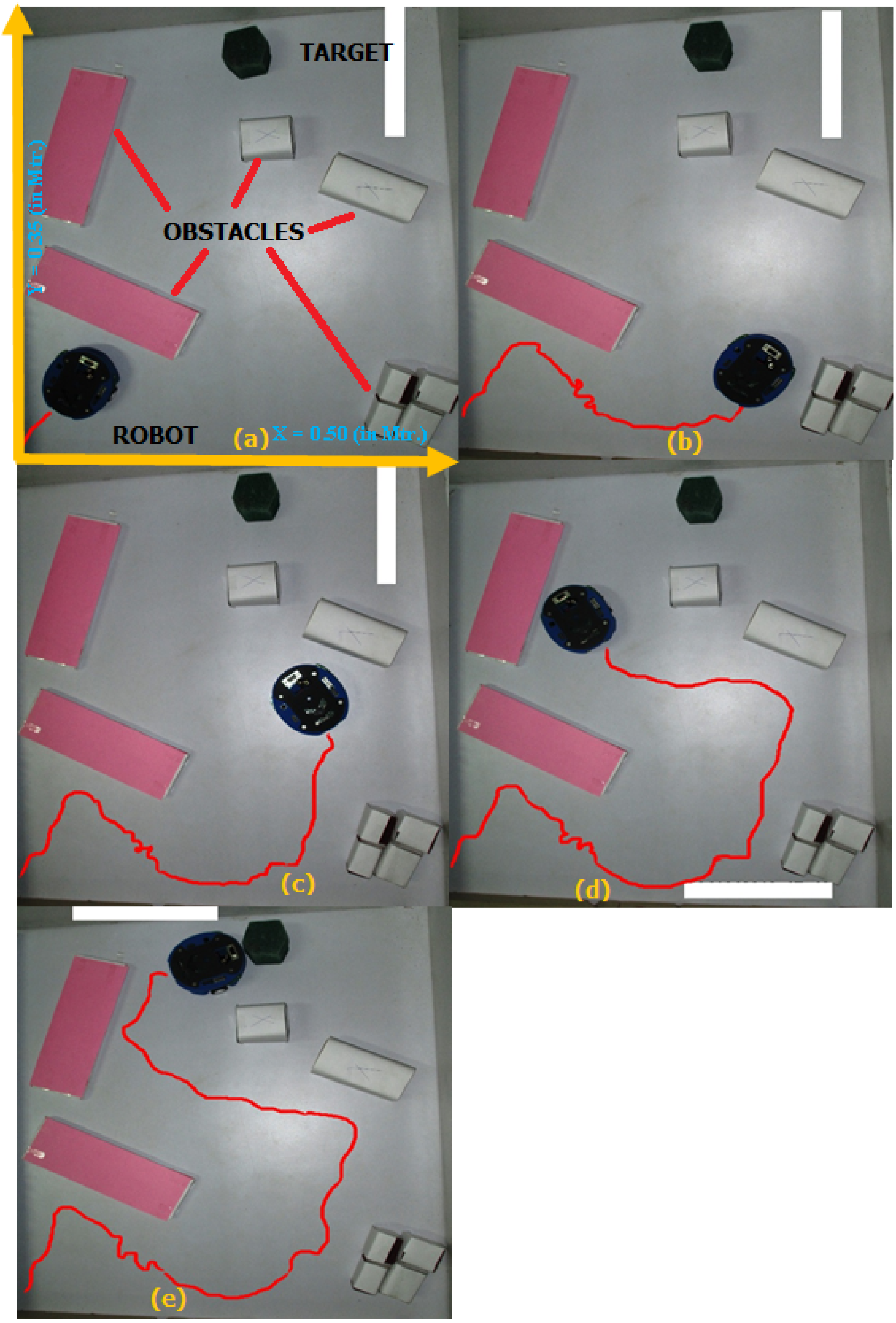


Figure 8.4: Path taken by the robot during experiment using Fuzzy Type-2 controller

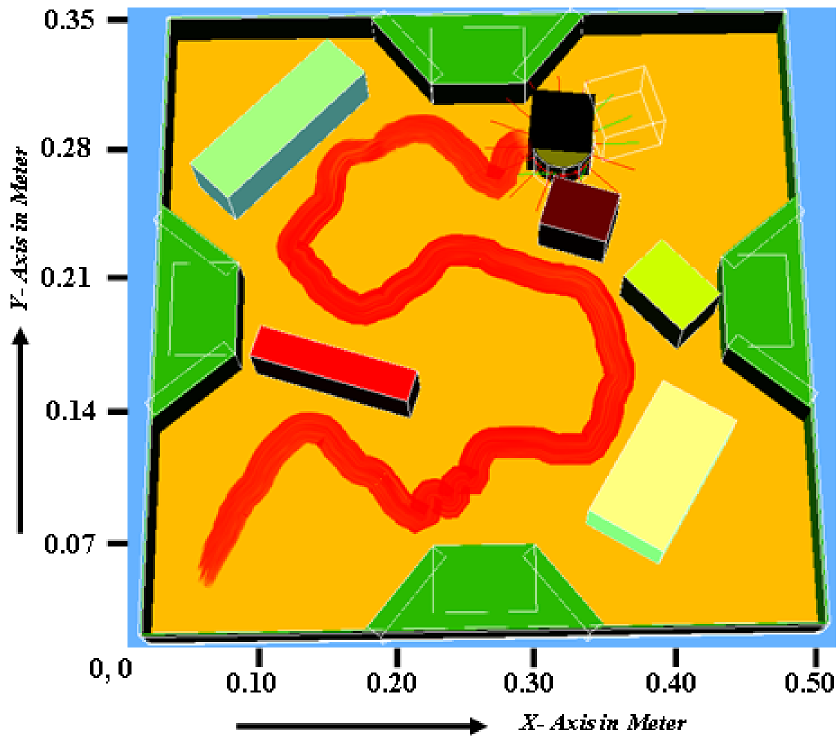


Figure 8.5: Path taken by the robot during simulation in WEBOTS for RNN

messy environment. When robot move from the source to the goal this algorithm provides smother and faster navigation strategies for mobile robot using RNN learning algorithm. The results show that more improvement in the results can be achieved than previous two methodology and comparison is represented in Table 8.1. Simulation result using RNN is demonstrated in Fig. 8.5. The simulation result shown in Fig. 8.5 has been verified experimently (Fig. 8.6) to show the efficiency of the developed navigational controller.

In chapter eight, hardware aspects of the Hemisson robot which is used for real time experiment has been presented. Proper Hardware implementation of model mobile robot leads to the successful experimental verification of specified navigational algorithms.

Table 8.1 demonstrates the comparison between three algorithms in terms of the path length and time taken during navigation from starting point to termination point. The above table also shows the error in percentage for each controller concerning the path length covered by the robot in both environment i.e. simulation and experiment.

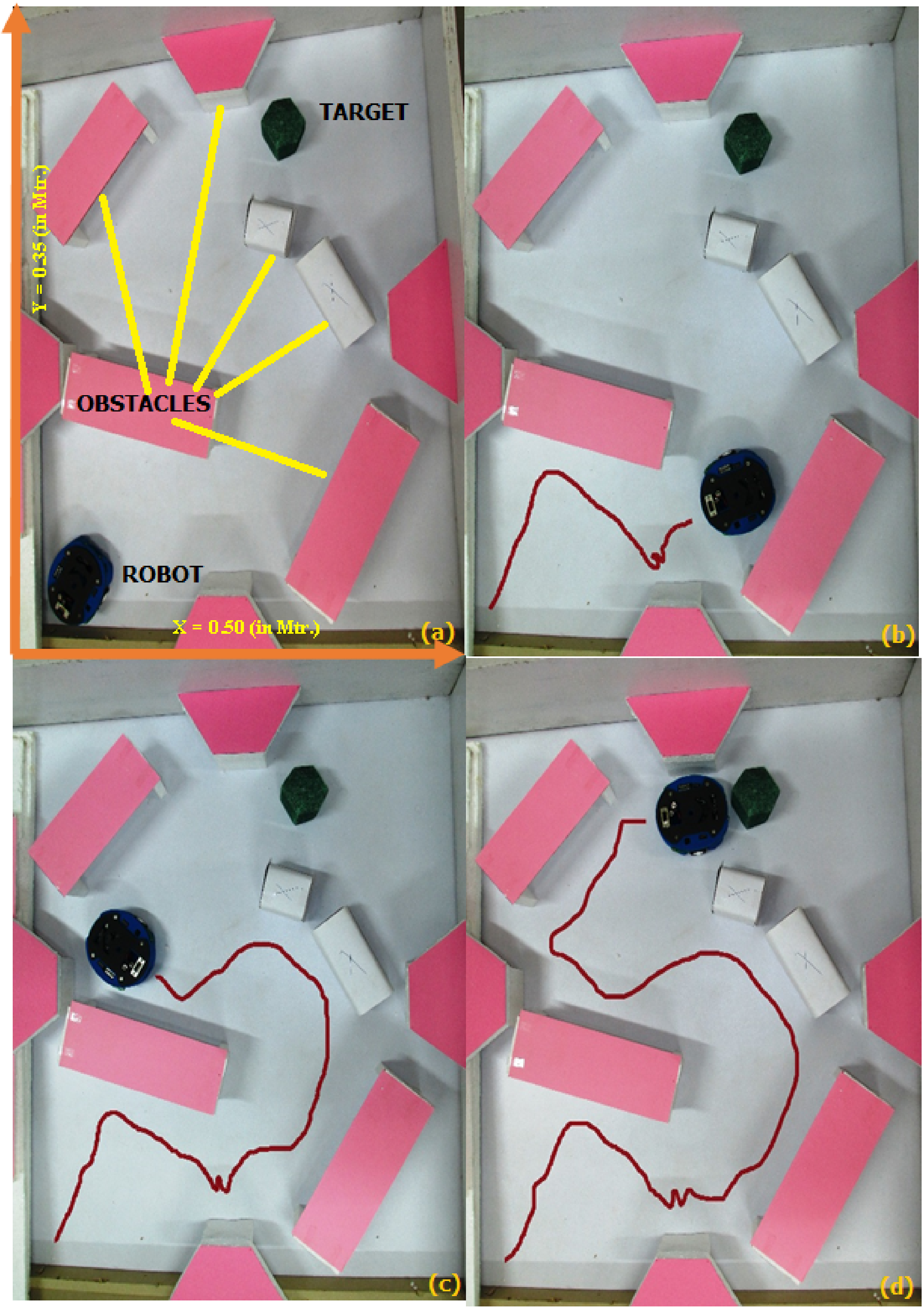


Figure 8.6: Path taken by the robot during experiment using RNN controller

Table 8.1: Represents the Comparison between simulation and experimental results

Sl. No.	Algorithm	TSR (P)*	ESR (P)*	TSR (T)*	ESR (T)*	ERROR
1	Using FLC	*0.796*	*0.804*	*00:50:960*	*00:52:524*	*1.0050*
2	Using T-2 FLC	*0.753*	*0.760*	*00:46:600*	*00:47:760*	*0.9210*
3	Using RNN	*0.739*	*0.745*	*00:28:192*	*00:28:876*	*0.8053*

"TSR (P)" = Theoretical Simulation Result Related to Path Length (in meter).

"ESR (P)" = Experimental Simulation Result Related to Path Length (in meter).

"TSR (T)" = Theoretical Simulation Result Related to Time Taken (in minute).

"ESR (T)" = Experimental Simulation Result Related to Time Taken (in minute).

"ERRORS" = Between Path Length i.e. TSR and ESR

8.1 Discussion

The fuzzy logic method is supposed to obey human decision making command but it does not assurance an optimum path generation. However, the error in the simulation and experimental analysis is low. The path generated by the robot is not an optimal one but it is generated depending upon the logic it works accordingly. Table 4.1 provides some of the values for the logical inputs and outputs. However, fuzzy logic also leaves some vagueness in its process. This is work out by the interval type 2 fuzzy logic controller. The results found through type 2 fuzzy logic controller are more satisfactory than simple fuzzy logic controller. The Fig 5.2 shows the path created by the robot using a type-2 FLC and it is superior than the path created simple fuzzy controller.

Further the recurrent neural network technique is a feedback learning mechanism and the accuracy is high for more number of iterations. The results shown in Fig 6.2(b) confirm the robustness of the RNN controller. The recurrent neural network model for mobile robot navigation is shown in Fig 6.5. In this model all the inputs and outputs of the network structure has been presented. This network is work on the principle of back propagation through time learning with feedback and feed forward algorithm both, accordingly accuracy is high.

8.2 Summary

The analysis of results depict that using fuzzy controller, the mobile robot takes a longer but safer path to reach the termination point. On the other hand, simulation based on type-2 fuzzy controller gives more accurate result than the fuzzy logic controller and also the path length is shorter for type-2 fuzzy controller than FLC. Similarly, the RNN back propagation algorithm, being a learning algorithm uses a shorter path than the previous two controllers as well as provides smother and faster navigation to the robot. In fact the RNN algorithm gives the optimal path length among all the three algorithms used.

Chapter 9

CONCLUSIONS AND FUTURE WORK

The major goal of this research work have been to find out powerful skills which enabling mobile robot to be explored safely in mobbed real world environment. From the proposed investigation illustrated in this thesis the conclusion and further work drawn are as follows:

9.1 Contributions

- ↪ With the reference of kinematic analysis of mobile robot, for demonstration of robot motion in global frame as well as the robot's local frame; a simple forward kinematic principle of motion has been assumed. Further, modelling of mobile robot is conducted by linking all kinematic constraints.

- ↪ In chapter four; based on sensory information, advanced the fuzzy reactive controller has been delivered progressive navigational rate to the robot at the time of obstacle avoidance, escaping from local minima problems, and seeking termination point during navigation in a complex hazardous terrain. Simulation and experimental results represents the degree of fractional optimization ability of the navigational controller, which settles the fuzzy controller that embedded with hybridized membership functions in a system to find the specified termination point with minimum path length and time.

- ↪ From Chapter five; planned fuzzy rule base navigational algorithm is combined with Type 2 fuzzy logic model to obtain more optimize wheels velocities and simply crisp value is the direct output. Comparisons between Type 1 and Type 2 fuzzy model for navigation purpose has also been presented.

↪ Next, a recurrent neural network navigational controller has been engaged with model for mobile robot navigation. From simulation results it was found that, the RNN is superior rather than the previous controller in terms of performance, feasibility and robustness.

↪ For real time experimental validation, Hemisson differential drive mobile robot has been taken into consideration. The proper interface between navigational methodology and hardware components of autonomous robot provides precious experimental results.

9.2 Conclusions

Through this research work, the effort has been made to solve a problem related to navigational path analysis as well as localization of mobile robots for different terrain. Thus, the conclusion drawn from this investigation are illustrated as follows.

↪ The vehicle configuration can't be obtained by sensor vision. So, it is essential to design highly constraints base kinematic and dynamic model for the robot. The kinematic model of the robot is principally the description of the allowable instantaneous motions with respect to its constraints. The planned navigational controller is claimed to be strong against the any changes in parameters of robot i.e. mass and inertia.

↪ The inference mechanism accompanied by projected fuzzy rule base (for both T1 and T2) gives a navigational control scheme, which indirectly addresses the demand of determining the sequence of actions such as to recognise the environment, to avoid obstacles and to achieve the goal successfully. The performance of the controller checked by the comparison between simulation and experimental results for different environmental situations in terms of paid time and path length.

↪ The IT2 Fuzzy control output increases the ability of the navigational controller to quickly react to sudden and unexpected changes in the input signal (e.g. when turning around corners and obstacle are present).

↪ RNN methodology also puts into practise to improving the navigational path analysis and localization performance of the robot through optimize learning and it gives satisfactory concern over FLC.

- ↪ This research is dedicated to evaluate the performances of proposed navigational controllers during navigation of mobile robot in different simulation and experimental environmental scenarios along comparison with previous research work for validation.

9.3 Further Works

The current effort advances design of sensible navigational controller which is based on artificial intelligence technique amplifying with human perception. Accordingly, the suggestions for future investigation are as follow:

- ↪ Further development of the methods may be essential for the avoidance of dynamic obstacles as well as for the other robots, which present in the working environment. So, the algorithms, which are more emphatic to deal with irregular real life conditions, may be introduced in near future.
- ↪ The navigational techniques developed in this research work are capable of detecting and reaching the static targets. Further modifications in these navigational techniques may be carried out so that the robots can not only detect dynamic targets but also reach them using an optimum path.

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DISSEMINATION

Papers Published/ Communicated in International Journals

1. D.R.Parhi and **Krishna Kant Pandey**, "A Review on Navigation System of Mobile Robot based on different technique with different Simulation software," *International Journal of Artificial Intelligence and Computational Research*, vol-5, No-2, ISSN: 0975-3974, pp.75- 84, 2013.
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3. Chinmaya Sahu, **Krishna Kant Pandey**, Dayal R Parhi, "Design and analysis of navigational controller for multi robots system using neural network," *Emerald Proceedings - International Conference on Intelligent Robotics, Automation and Manufacturing*, pp. 527-533, 2013.
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5. Alok Kumar Jha, **Krishna Kant Pandey** and Dayal R Parhi, "Fuzzy Logic based Intelligent Control of a Mobile Robot," *Proceeding of International Conference on Advance in Mechanical Engineering* , College of Engineering Pune (INDIA), May 29-31, 2013.